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RELIABILITY ASSESSMENT OF THE MARINER SPACECRAFT

PRC R-293

17 December 1962

Prepared for

Jet Propulsion Laboratory
Pasadena, California

By

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FOREWORD

In August 1962, a significant milestone in planetary research was reached when the Jet Propulsion Laboratory, of Pasadena, California, successfully launched an instrument-bearing payload on a trajectory that would ensure a fly-by encounter of the planet Venus. This spacecraft, designated "Mariner R," was designed to perform a number of scientific and engineering measurements and to communicate the measured data to earth.

Because of the continuing nature of research of this type, the reliability of the Mariner R spacecraft was considered to be a matter of definite interest, and an assessment of the spacecraft system was undertaken to ascertain its reliability strengths and potential weaknesses. To this end, JPL contract BU3-213751 was issued to Planning Research Corporation on 10 September 1962 to conduct such an assessment and to evaluate the spacecraft reliability in numerical terms. The findings of that assessment are presented in this report.

It is a pleasure to record that the efforts of the PRC assessment team were rendered all the more effective by virtue of the timely and close cooperation of the Systems Design Section of JPL. In particular, the vital task of coordinating the sundry details of project liaison was ably handled by Dr. Elizabeth Baxter, of the Systems Design Section.

The authors wish to acknowledge the considerable assistance received from other members of the PRC staff in the conduct of this study. Specific mention should be made of the efforts of H.B. Battey, J.P. Francis, J.M. Lambert, and E.H. Spoehel. The constructive guidance of G.R. Grainger was employed throughout the project.

ABSTRACT

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The results of a quantitative reliability assessment of the Mariner spacecraft are reported, and conclusions regarding the reliability of the spacecraft subsystems are stated. The reliability figure-of-merit approach is utilized to provide a realistic evaluation of the probabilities of successfully achieving the various mission objectives. In addition, classical reliabilities of events and functions are computed on a parts count basis so that specific areas of the spacecraft can be examined in more detail. Through consideration of the reliability assessment results, the most applicable testing techniques are outlined, and a few areas are identified as the most likely candidates for limited design re-evaluation. Complete data on failure-rate estimates and parts counts are included.

AUTHOR

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I. INTRODUCTION

Any attempt to assess the reliability of a complete system such as the Mariner R spacecraft will inevitably give rise to a number of questions regarding the details of the assessment method and the composition of the over-all results. This report represents an effort to answer such questions and to furnish a body of information and data that will permit continued analysis of the system reliability. The study is directly concerned with the Mariner R spacecraft as configured for the 1962 Venus probe, and has been conducted, insofar as possible, without regard to the current results of the actual flight underway during the period of the study.

A. Background

A qualitative reliability assessment of Mariner R was undertaken in July 1962, and sufficient analysis of the system was made to formulate a mathematical reliability model tailored to the design of this particular spacecraft. The results of that assessment were reported in Mariner R Reliability Model Formulation and Qualitative Assessment (Planning Research Corporation, R-266), dated 24 August 1962. That report, prepared under contract to the Jet Propulsion Laboratory, set forth a basic mathematical model designed to show the reliability of the system in terms of a figure-of-merit which would account for the many possibilities of partial achievement of the mission objectives. The report predicted, on a qualitative basis, that a simple "parts count" reliability estimate of Mariner R would reveal a low probability of complete success over the entire mission.

The study which is the subject of this report commenced in late September 1962. The prime study objective has been the exercising of the reliability model to obtain numerical estimates of reliability. To yield meaningful results, the study effort required (1) more detailed examination of the spacecraft design documents and (2) refinement of the model to incorporate the greater detail. Close cooperation between the

Systems Design Section of JPL and the reliability assessment team at PRC has been maintained throughout the course of the work.

B. Problem Statement

As was just indicated, the principal study objective has been the exercising of the reliability model and the computation of numerical reliability estimates for the Mariner R spacecraft. The figure-of-merit concept has been employed, but a secondary aspect of the problem has been the determination of significant classical reliability estimates for a variety of spacecraft subsystems and mission events. The final objective of the assessment has been the formulation of a set of test program recommendations and the establishment of a test philosophy applicable to this particular system.

C. Study Approach

The basic approach utilized in the Mariner assessment requires two fundamental ingredients. The first is a compilation of estimates of the probabilities that the various equipments on board the spacecraft will be operable as required throughout the mission. The second is a set of discrete and continuous value functions that establish the relative worth of the mission objectives and describe the manner in which the value of each objective accrues as a function of time. Given these two groups of information, it is then possible to merge them by appropriate integration methods to show the expected or average value that will accrue throughout a mission, culminating in a final total expected mission value or figure-of-merit.

The determination of a set of value functions was accomplished by the System Design Section of JPL in accordance with a format designed jointly with the study team from PRC. These value functions apportion the total mission value (normalized to unity) over each of the mission objectives.

The computation of the probabilities that specific equipments will be operable at various times during the mission is a composite task that can best be understood by noting the three principal elements of which it is comprised:

1. The spacecraft subsystems must be sectioned and recombined into reliability units. These units consist of collections of components or piece parts which always function together and which depend upon each other for any useful output.

2. Each unit must be analyzed to determine its parts count. By applying available failure-rate data to this parts complement, the failure rate of the unit can be calculated.

3. Through study of the failure effects of each unit and the demands of the mission-time profile, a schedule of unit requirements can be prepared. This schedule delineates--for each mission objective--which units are needed, at what points in the mission, and for what time periods.

These three steps having been taken, it is a relatively straightforward exercise to combine the unit failure rates for the various groups of units identified from the schedule and compute survival probabilities for the periods called out by the schedule. Redundancies must, of course, be included.

The following mission objectives were considered to have significant value for the purposes of the assessment:

1. Acquisition
2. Vehicle tracking
3. Midcourse maneuver
4. Engineering data
5. Cruise science data
6. Planet science data
7. Planet encounter with tracking

Computation of the probabilities that these objectives could be met at various points within, or continuously throughout, the mission constituted a major portion of the study effort.

D. Organization of the Report

The study approach sketched above suggests the manner in which presentation of the results is organized. Initially, a "quick look" at the study is provided the reader in the form of a condensed summary of the more important numerical results. This appears in Section II and is preceded by a listing of general assumptions which delimit the study and establish the necessary boundaries on the scope of the work.

Before any attempt to refine or exercise the mathematical model can begin, it is necessary to carry out the unitization process that assembles the spacecraft hardware and circuitry into reliability blocks or units. Section III discusses the manner in which this was accomplished and illustrates the principal interconnections of these reliability units. The effects of unit failures are an essential part of this discussion.

Section IV describes the employment of these units in the reliability computations and presents the full set of numerical results. This section has been divided into a number of subsections in order to compartmentize these important facets of the study. Applicable failure rates are tabulated in the beginning of the section and the unit configuration for a normal (perfect) mission is specified in detail. Next, the simplified mathematical model is derived, and the distinctions between classical and value-weighted (figure-of-merit) reliabilities are clarified. At this point, the value apportionment functions are presented and the value accrual concept is explained. In subsection IV.E the details of the calculations leading to the spacecraft reliability estimates are set forth. Classical reliability estimates are separated from those which establish the figure-of-merit.

The remainder of the main body of the report consists of recommendations and conclusions. The first of these, concerned solely with testing considerations, are given in Section V. Other conclusions, derived from the reliability assessment, are listed in Section VI.

Two appendices have been included in the report to supplement the description of the assessment details. Appendix A is a complete tabulation of the parts counts for all of the units. Appendix B treats the somewhat controversial subject of parts failure rates, and discusses the philosophy behind the failure-rate assignment on which the numerical computations have been based.

II. SUMMARY OF NUMERICAL RESULTS

The exercising of the mathematical model of the Mariner spacecraft allows considerable latitude with respect to the range of questions that can be answered. However, to conform to the limits of this study, results were confined to those considered both interesting and significant. These results include classical reliabilities unmodified by any value-weighting functions. More importantly, the results of a reliability figure-of-merit analysis have been derived, and probabilistic value elements are computed and integrated to give an over-all reliability figure-of-merit for the spacecraft. Prior to summarizing these results, it is well to review some of the basic assumptions which have influenced the character of the study and which must be borne in mind in any attempt to assess the implications of the reliability predictions that have been calculated.

A. General Assumptions

Many specific assumptions have been made with regard to the various operational configurations and situations that have been analyzed. These specialized suppositions are brought to light in the discussions that surround the section of the analysis to which they apply. There are, however, certain general assumptions which delimit the entire study and which serve as "ground rules" in obtaining and interpreting the results. These assumptions are listed here.

1. Launch phase failure possibilities are not considered. All equipment and all piece parts required for the Mariner mission after injection are assumed to be operable throughout the launch phase, and no incipient failures have resulted from the launch stresses.

2. Scientific experiments are completely reliable. Except for certain hardware associated with the planet scanning function, it is assumed that none of the scientific experiments fail during the mission. Thus, loss of value to be returned from these experiments is a consequence of equipment failure outside the experimental hardware or circuitry.

3. Engineering measurement transducers are completely reliable. This is similar to assumption 2, but refers to the equipments (such as temperature or position transducers) that provide the unconditioned signals for telemetry purposes.

4. The trajectory of the space probe after injection is correctible by the midcourse maneuver. The two cases which are disallowed by this assumption are, first, that the required correction is beyond the capability of the midcourse motor and, second, that injection was accomplished so accurately as to obviate the requirement for a midcourse correction.

5. The mission period is 2590 hours. This variable, which depends to a large extent on the time of launching, has been fixed at 2590 hours. At the end of this period, it is assumed that the planet-encounter event occurs over a 30-minute time span.

6. Part failures are catastrophic. Degraded operation of piece parts is not considered. It is assumed that a failed part is completely inoperable and will remain inoperable from the time of failure throughout the balance of the mission.

7. Part failures are random in time. This assumption is predicated on the absence of "burn-in" or "wear-out" failure mechanisms, and allows the application of the exponential failure law and the exclusive use of random failure rates.

8. All parts are exposed to the same stress. The selected failure rates are based on the assumption that each piece part is stressed to 25 percent of its design rating and operates in an unchanging ambient temperature of 35°C.

With the foregoing assumptions as a background, the principal results of the study are summarized in the following subsection.

B. Summary of Classical Reliabilities

In a classical reliability analysis it is customary to establish some minimum level of performance as the criterion of success or failure. No attempt has been made to establish such a degraded level here, because the figure-of-merit analysis automatically introduces the judgment necessary to distinguish between the desirability of various operational states, and quantifies the performance levels on a rational basis. Accordingly, the reliability estimates summarized below reflect a philosophy which demands that every part under consideration operate for the specified period with no failure. The events or functions described below represent those which are of interest and which can have a significant bearing on the total mission.

1. Solar panel deployment: .9994 probability of success. This includes equipment required for panel erection and the effect of the redundant ground command.

2. Power supply: .7159 reliability through entire mission.[1] This includes equipment used for inversion to 2400 cps and to 400 cps power.

3. Transponder (coherent): .6876 reliability through entire mission. The estimate is for the phase-locked, two-way mode of operation only.

4. Transponder (noncoherent): .8530 reliability through entire mission. This equipment covers the use of the standby oscillator and no reception of ground signals.

5. Sun tracking: .9026 reliability through entire mission. The estimate assumes acquisition has occurred, and covers the maintenance of stability about pitch and yaw axes.

6. Attitude stability: .3172 reliability through entire mission. This is similar to function 5, but includes control about all spacecraft axes and the hinge axis as well.

7. Midcourse maneuver: .8000 probability of success. This includes all spacecraft equipment (such as attitude control and power) associated with the execution of the midcourse maneuver.

8. Command capability: .2327 reliability through entire mission. This estimate covers the transponder as well as the command detector and decoder.

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[1] "Entire mission" as used here includes the encounter period.

9. Central computer and sequencer: .7078 reliability through entire mission. The CC and S equipment only is involved in this estimate.

10. Science measurements: .4561 reliability through entire mission. This estimate includes the Science Data Conditioning System and switching units required for cruise and planet science.

11. Data encoder: .1522 reliability through entire mission. All commutator decks, modulators, synchronizing code generator, and subcarrier sources are included in this estimate.

Considering the entire spacecraft, it is of interest to inquire about the reliability of all of the equipment needed through various points in the mission. This has been done, and typical results range from .9972 reliability through the first hour to .6931 reliability through midcourse maneuver, with a final value of .0104 reliability through encounter. Except for a few step changes occurring around the time of the midcourse maneuver, the general trend of spacecraft reliability is exponential with time. This is to be anticipated, inasmuch as the exponential failure law has been used and relatively little redundancy exists within the system.

C. Summary of Figure-of-Merit Results

A prerequisite to the figure-of-merit reliability analysis is the assignment of a quantitative estimate of value to each of the various mission objectives. Depending upon the nature of the objective, a value assignment may take the form of a continuous function of time or it may accrue instantaneously in the manner of an impulse function. It is convenient (although not essential) that these value functions be normalized so that the sum of the time integrations of all value functions, taken over the mission period, will equal unity. If the probabilities of equipment survival are appropriately modified by these mission-objective value functions, the results can be viewed as the expected[1] value to be derived from a series or group of similar missions.

[1] Throughout this report the words "expected" and "average" are used interchangeably to denote the statistical mean or expectation.

The figure-of-merit reliability analysis of the Mariner mission indicated that the expected mission value is .4151 as compared to the maximum or desired value of unity. The expected value elements corresponding to the various mission objectives are summarized in the following table:

Mission Objective	Assigned[1] Value	Expected Value
Midcourse maneuver	.1510	.1208
Sun and earth acquisition	.0580	.0485
Vehicle tracking	.1160	.0876
Engineering data	.1400	.0811
Cruise science data	.1510	.0378
Planet encounter	.0930	.0147
Planet science data	.2910	.0246
Total expected value	1.0000	.4151

It should be remembered that, because many of the mission objectives are of a "one-shot" nature, the idea of an "expected" value cannot be applied to a single mission in the strict sense. Any single mission will very probably result in a total value return that is much higher or much lower than the "expected" value of approximately 42 percent. The prediction is, however, a much more realistic measure of mission success than that derived using the classical reliability approach.

[1] Alternatively, this quantity could be denoted as the maximum value.

III. UNIT SELECTION AND FAILURE EFFECTS

A. Selection Method

In conformance with the previously developed reliability model, the Mariner spacecraft subsystems have been segregated into reliability units. A reliability unit comprises a group of equipments and/or components that always work together. Because of this definition of a unit, the failure of a part or component within any unit is usually considered a complete failure of that unit.

The unit selection developed for this study supersedes and refines the unit listing that was used in the original model formulation study (cf. subsection I.A). That earlier study anticipated that a refinement of the unit breakdown would be required following a detailed examination of the subsystem schematic diagrams. This refinement has increased the number of units identified from 58 to nearly 100. It will become clear later in this description that many of the selections could have been combined, thus reducing the total number of units; however, an artificially large complement of units has been retained in order to permit a closer scrutiny of those areas that might prove to be potentially poor from a reliability standpoint. Each unit is identified in the exhibits that follow by a three-digit number in accordance with the scheme developed for the model. In this scheme the first digit refers to the major function served by the unit. The next two digits provide serial identification only and have been assigned arbitrarily but in ascending sequence to the units within a function. The functional identifications are listed:

100 - Science Measurements
200 - Subcommutated Engineering Data
240 - Analog and Digital Engineering Data
280 - Subcarrier Generation and Modulation
300 - Ground Command
400 - Central Computer and Sequencer
500 - Power Supply
600 - Attitude Control
700 - Midcourse Maneuver
800 - Transponder
900 - Thermal Control and Miscellaneous

B. Reliability Units

The units for each of these major functions have been arranged in a manner that depicts their interdependence, to the extent possible, from a reliability standpoint. These pictorial representations will be discussed individually.

1. Science Measurements

The science measurements have been segregated into three groups as shown at the left-hand side of Exhibit 1. The uppermost group consists of digital science measurements such as ions, particles, and cosmic dust. In addition, the magnetometer scale change is included with this group. The plasma and magnetometer measurements comprise the second group, which, together with the first, constitutes the cruise science measurements. Infrared and radiometric measurements form the third group, which, while energized throughout the mission, are not utilized until planet encounter.

The cruise measurements are relayed on by unit 101 and are conditioned by units 104 and 105. The digital experiments are not dependent upon the A-D converter, unit 105, but they would be lost in the event of a failure of unit 104, the D-D converter. The analog experiments, for both the cruise and encounter phases, are dependent upon unit 105. Unit 102 introduces the planet scanning logic, and unit 103 accounts for the necessity of turning on the planet science at the appropriate time.

All science measurements are wholly dependent upon the remaining four units, 106 through 109. Units 106 and 107 were derived from the Science Data Conditioning System, and unit 108 is a combination of components from the SDCS and the science power switching unit. Unit 109 introduces the effect of the science transformer rectifier.

The specific consequences of a catastrophic failure of each of the units are brought out by an examination of the exhibit.

a. Unit 101

A failure of these relays will de-energize the cruise science experiments. Planet science experiments will be unaffected.

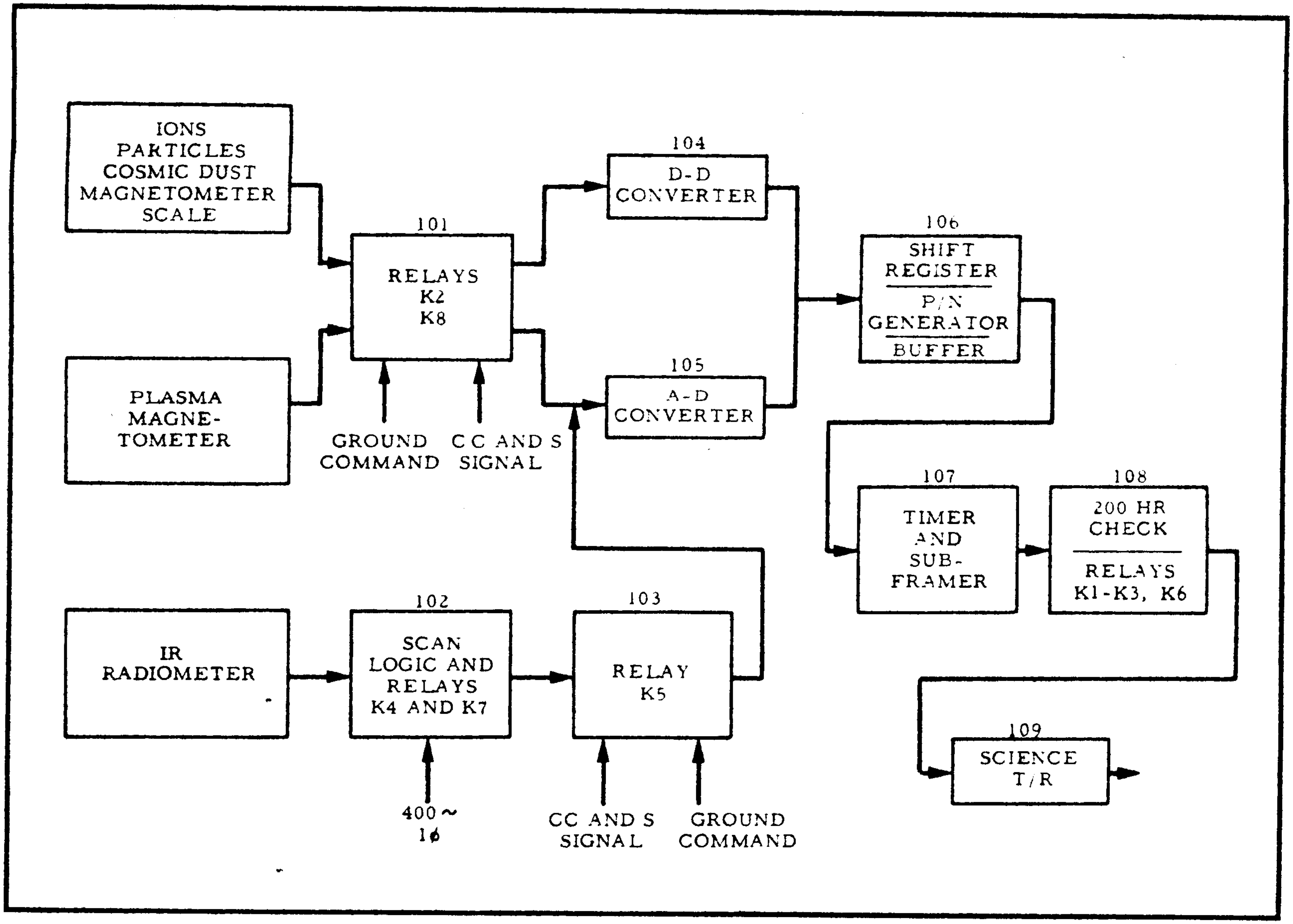

EXHIBIT 1 - SCIENCE MEASUREMENTS

b. Units 102 and 103

These units, if failed, will cause the loss of the planet science experiments. There will be no effect on cruise science.

c. Unit 104

A failure of this converter will lose the digital cruise science experiments. It should be noted that these experiments include the setting of the magnetometer scale, and the loss of this function will have special effects which might need consideration.

d. Unit 105

The A-D converter is responsible for the correct encoding of the analog cruise science experiments as well as the planet science experiments. A loss of this unit would destroy all but the digital science experiments.

e. Units 106, 107, 108, and 109

From the standpoint of failure effects, these units could be combined. A failure of any of them will cause the loss of all science measurements.

2. Subcommutated Engineering Data

Approximately 31 channels of spacecraft status measurements are processed through equipment that has been separated into reliability units in the manner shown in Exhibit 2. The four C deck words are subcommutated at the medium rate, which is 1/10 of the main commutation rate. These medium-rate channels include measurements of the transponder performance and, in addition, a thermal control louver position indication. The D, E, and F deck channels are subcommutated at the low rate, which is 1/100 of the main commutation rate. D deck is responsible for the telemetry of a variety of measurements including solar panel voltages and currents, omni antenna power, attitude control nitrogen pressure, and two reference measurements. The E and F decks are assigned to the telemetry of various spacecraft temperatures

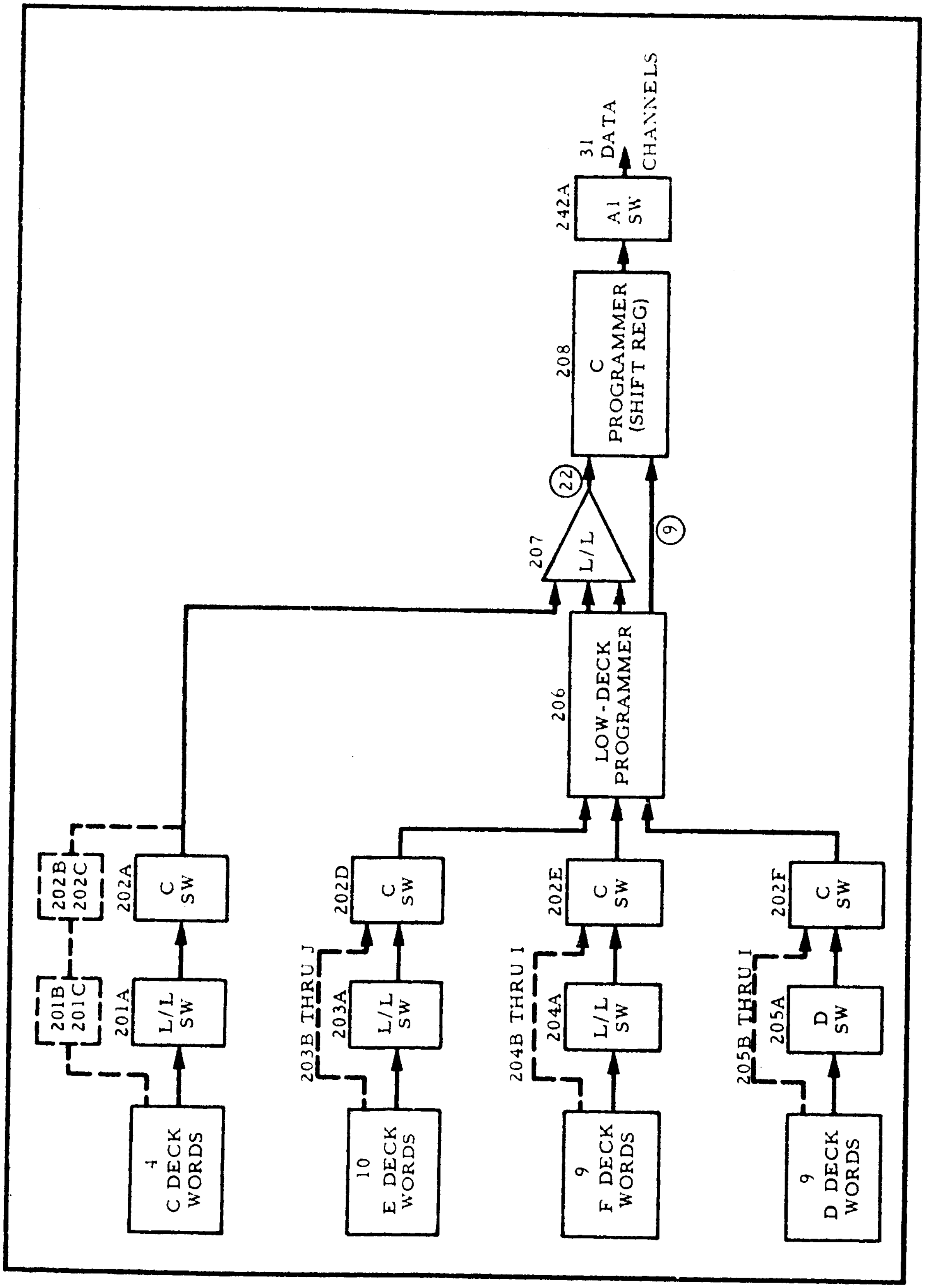

EXHIBIT 2 - MEDIUM- AND LOW-RATE ENGINEERING DATA

such as the solar panel temperatures, the electronic assembly temperatures, and temperatures of the battery, earth sensor, propellant tank, and other components.

All of these channels generate data that is analog in nature and, hence, must be routed to the analog-to-digital converter not shown on the figure. In this time-division multiplexing scheme, each channel must be sequentially connected to the output line, and this is accomplished through the programmed operation of a bank of solid-state switches. The closure of these switches is not maintained through the entire wordtime, but rather is only momentary, and the transmitted sample voltage is "boxcarred" by the analog-to-digital converter. These ac-coupled switches are unlikely to fail in a closed position, and, consequently, the most likely failure mode will be one in which only a single channel is affected. For this reason each switch is shown in the diagram as being associated with only a single data channel.

Deck C includes a bank of three low-level switches identified as units 201A through C. All channels routed through this deck utilize the normal commutation switches; these have been individually unitized as 202A through F. Decks E and F consist solely of banks of low-level switches. Units 203A through J identify the deck E switches, and units 204A through I specify the deck F switches. Deck D channels do not require low-level switching, and units 205A through I identify the switches for this deck. The sequential switching of the low-rate decks is accomplished through a logic matrix which is identified as unit 206, the low-deck programmer. The low-level signals emanating from the channels of decks D, E, and F are amplified and conditioned by the low-level amplifier, unit 207.

All low- and medium-rate measurements are dependent upon the proper operation of a shift register, which is shown in the figure as unit 208, the C deck programmer. The introduction of the low- and medium-rate data to the analog-to-digital converter is accomplished through unit 242A, which is a switch associated with high-rate deck A.

The analysis of the failure effects can be discerned from an examination of the exhibit.

a. Units 201 and 202A through C

A failure of any of these switches will cause the loss of a C deck word. It should be remembered that these are medium-rate words.

b. Units 202D, E, and F

Failure of unit 202D will cause the loss of all E deck words. Similarly, a failure of unit 202E will prevent transmission of any F deck words, and, correspondingly, a failure of unit 202F will lose all of the D deck words.

c. Units 203, 204, and 205

A single failure of any of these switches will cause a loss of an E, F, or D deck word, respectively.

d. Unit 206

The loss of the low-deck programmer will, in general, cause a failure of the low-rate commutation. Consequently, transmission will be impaired for all D, E, and F deck channels.

e. Unit 207

A failure of unit 207, the low-level amplifier, will prevent transmission of any of the low-level signals. These include all the C, E, and F deck words.

f. Unit 208

The C deck programmer, consisting of a shift register, has discernible failure modes; however, for the purposes of this study it is assumed that any failure of a component assigned to this unit will result in a total failure of the subcommutation function and a consequent loss of all medium- and low-rate engineering data.

g. Unit 242A

This switch, which gates all the subcommutated data, is also included in the parts count for unit 283, which will be shown on another figure. The duplication is intentional, because the failure mode

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considered here is that in which the switch remains open. It is clear that such a failure would lose all of the subcommutated engineering data.

3. High-Rate Engineering Data

The medium- and low-rate engineering data are commutated through the A deck which, together with the B deck, forms the high-rate commutator. There are 17 active high-rate channels producing analog data, and one high-rate channel is devoted to the transmission of digital data. These are shown in Exhibit 3. The high-rate analog words have been divided into two groups, because nine of them require isolated power supplies, whereas eight do not have this requirement. The transducers that demand isolated power supplies include the gyros, sun sensors, earth brightness, and the AGC and phase-error measurements for the transponder. The remaining high-rate analog channels are assigned to the measurement of battery voltages and currents, antenna hinge quantities, and pressures associated with the midcourse maneuver propellant.

Engineering data developed in the digital format is comprised of blip events which are generated to indicate the successful deployment of the solar panels, the receipt and execution of ground commands, the actuation of pyrotechnic devices, and other important one-shot events. The dependence of certain high-rate words upon isolated power supplies is shown by units 241A through I. The A and B deck switches, like those of the medium- and low-rate commutation decks, are ac coupled. Certain of these switches, identified as units 242B through J, are assigned to the commutation of those high-rate words that require isolated power supplies. The other high-rate analog words are commutated through A and B deck switches identified as units 242K through R. These analog words are put into the pulse code format by means of the A-D converter, unit 243.

The event blips are stored in registers, units 244, 245, 246, and 247. These digital event registers are interrogated on a programmed basis by the event sequencer, unit 248, and their contents are emptied sequentially into the transfer register, unit 249. The digital data is

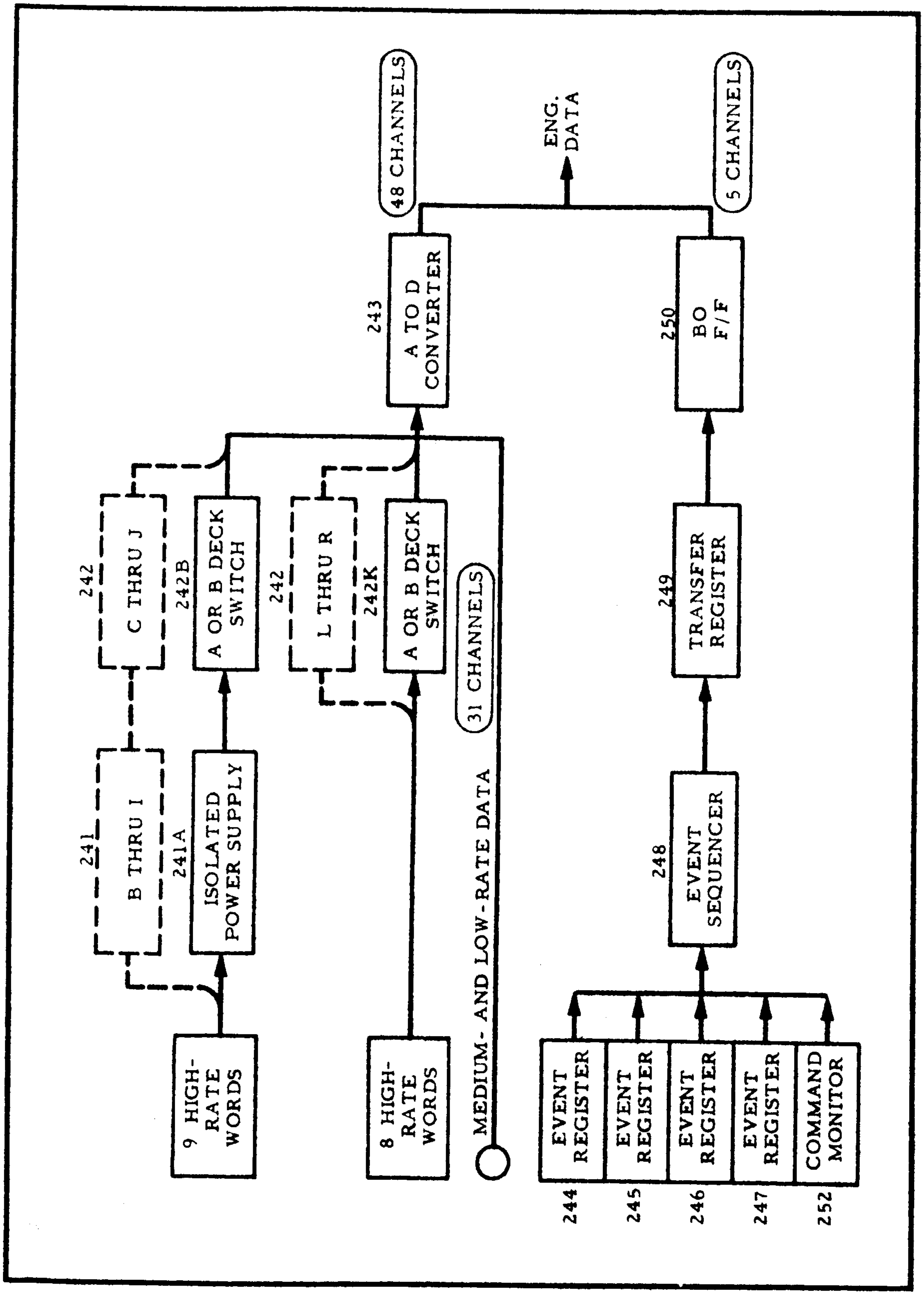

EXHIBIT 3 - ENGINEERING DATA

gated out through one of the flip-flops in the A/B programmer (shift register for A and B decks) and this dependence is indicated by the appearance of unit 250. Unit 252 groups together the special equipment required for the command detector monitor. Most of this monitor equipment is outside of the data encoder and consists of the special counter required for monitoring the VCO frequency together with the logical circuitry which indicates the state of the command phase lock.

Proceeding as before, it is possible through the use of Exhibit 3 to determine the first-order effects of single unit failures.

a. Units 241A Through I and 242B Through J

A single failure of any of these units will cause the loss of one of the nine high-rate words that require isolated power supplies.

b. Units 242K Through R

The failure of one of these switches will impede transmission of one of the remaining high-rate analog words.

c. Unit 243

An impairment of the A-D conversion function will result in the compound loss of all medium- and low-rate data together with all high-rate analog data. The transmission of digital data from the event registers will not be impaired.

d. Units 244, 245, 246, and 247

An event register failure will cause the loss of the blip event data associated with that register. No other data will be lost.

e. Units 248, 249, and 250

These units could be combined, and it is clear from the diagram that the loss of any one of them will preclude the transmission of the digital event data as well as the command monitor data.

f. Unit 252

A failure within this unit loses the command monitor data only.

4. Subcarrier Generation and Modulation

Engineering data and science data, as generated by the units just described, are selectively modulated onto a suitable subcarrier and mixed with a special synchronizing signal prior to transmission via the transponder. The reliability units involved in this process are shown in Exhibit 4, together with the portions of the commutator that are common to both engineering data and science measurements. The mode logic and transfer equipment, identified in the figure as units 280 and 281, are concerned with the proper sequencing of science and engineering data as demanded by the mission profile. All data is in pulse code format and is impressed on a subcarrier by means of the data modulator, unit 282. Unit 283 shows the dependence for data transmission on the shift registers which make up the master counter, the programmer for decks A/B, and the 24-word science frame timer. Because of the possible failure modes of unit 283, it is not realistic to assume that a failure of a single component within this unit will prevent the transmission of all engineering and science data.

The programmer and timer, consisting of a total of 44 flip-flops in a shift register arrangement, operate by inserting a "one" in the beginning of the register and progressively advancing this "one" through all stages of the register. If any flip-flop in the register fails in the "one" state, then succeeding clock pulses will advance this "one" through the register along with the normally inserted "one." This type of operation would result in simultaneous closure of two switches for each commutation step, and it is evident that all data received would be garbled. This condition would, of course, persist and preclude any further transmission of data.

On the other hand, if a flip-flop were to fail in the "zero" state, operation would be normal until the inserted "one" had progressed as far as the failed flip-flop, after which no data would be transmitted for the balance of the frame. This failure would not prevent the resetting of the decks, however, and the reception of data would continue from those channels that occupy slots in the frame ahead of the failed channel. This condition would give rise to many possible failure states, each

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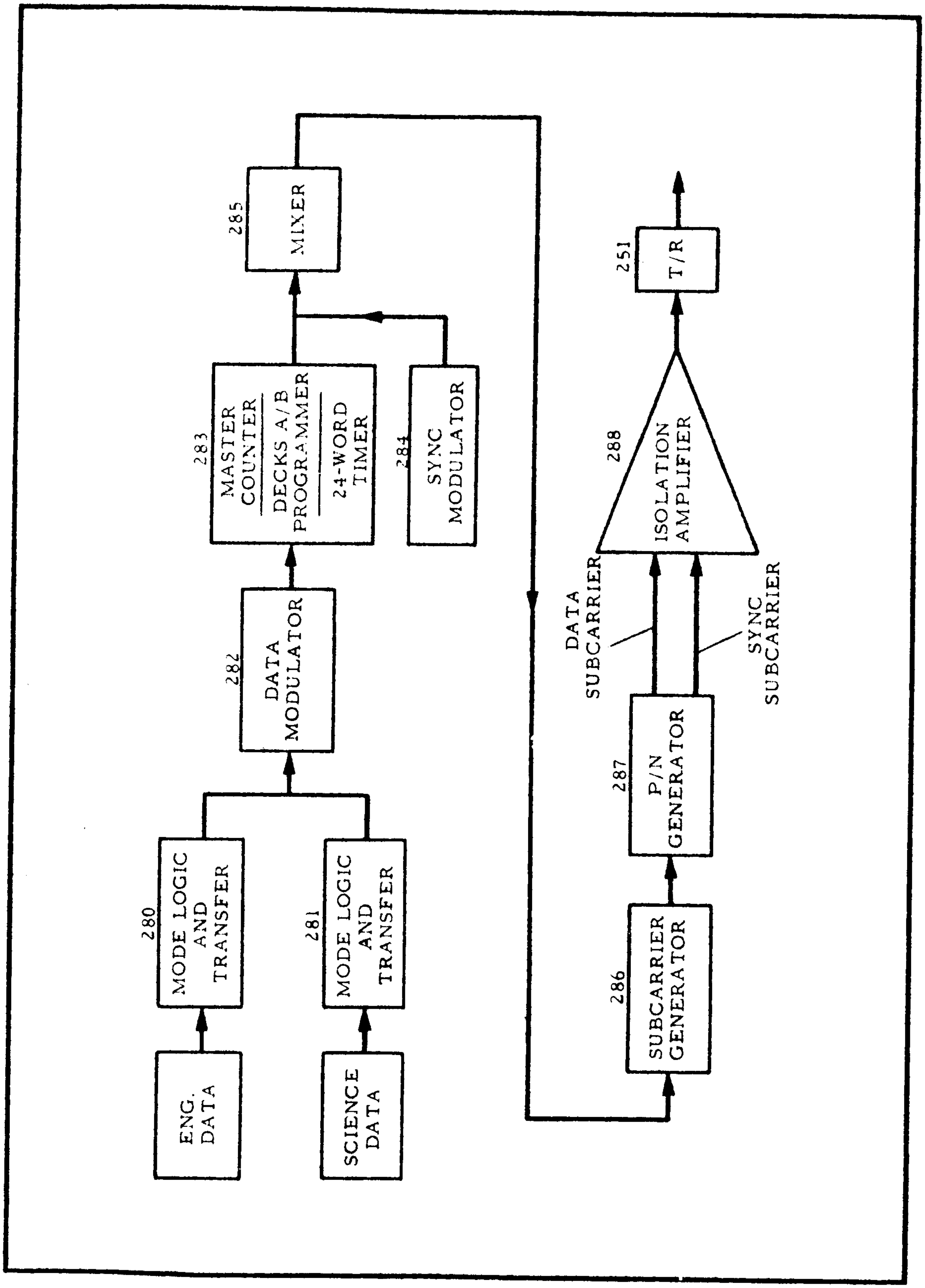


EXHIBIT 4 - SUBCARRIER GENERATION AND MODULATION

dependent upon the point in the data frame at which the failure occurred. Because of the symmetry of the equipment, there is no reason to suspect that the failure would occur at any one frame slot with more likelihood than any other. Inasmuch as half of the failure states result in a total loss of data, and the other half result in a loss that can vary from one word up to totality, the simple assumption is made that the "average" failure would result in a 75-percent data loss.

The modulation equipment for the sync code is shown as unit 284, and the mixer for the sync and data subcarriers is unit 285. The sync modulation process is not required for the transmission of data and, accordingly, unit 284 is positioned in the diagram in a manner to indicate this lack of dependence. On the other hand, the sync code generation is accomplished by the P/N generator, unit 287, and this device is also responsible for the master counter drive function, which makes all data transmission completely dependent upon it. Unit 286, the subcarrier generator, includes the countdown circuitry which produces the subcarriers. Complete dependence of the data transmission function on the data encoder power supply is shown by unit 251, and a similar dependence is indicated by unit 288, the isolation amplifier.

The diagram discloses that there are relatively few distinguishable effects of single unit failures. These are discussed below.

a. Units 280 and 281

In this case the failure of each individual unit will result in the loss of engineering data or science data, depending upon which unit has failed. It will be recognized that both units actually constitute the same equipment. An effort has been made here to account for two possible failure modes.

b. Unit 282

The loss of this unit would prevent the transmission of either the engineering or science data, but it should be observed that the transmission of the properly modulated sync subcarrier would continue.

c. Unit 283

As discussed above, a failure of this unit is considered to result in the loss of 75 percent of the engineering and science data. Again, the sync subcarrier continues to be transmitted.

d. Unit 284

A failure of the sync modulator would not interfere with the transmission of data; however, the primary data-sychronizing reference would be lost, and considerable time and effort would have to be expended in decoding the received data.

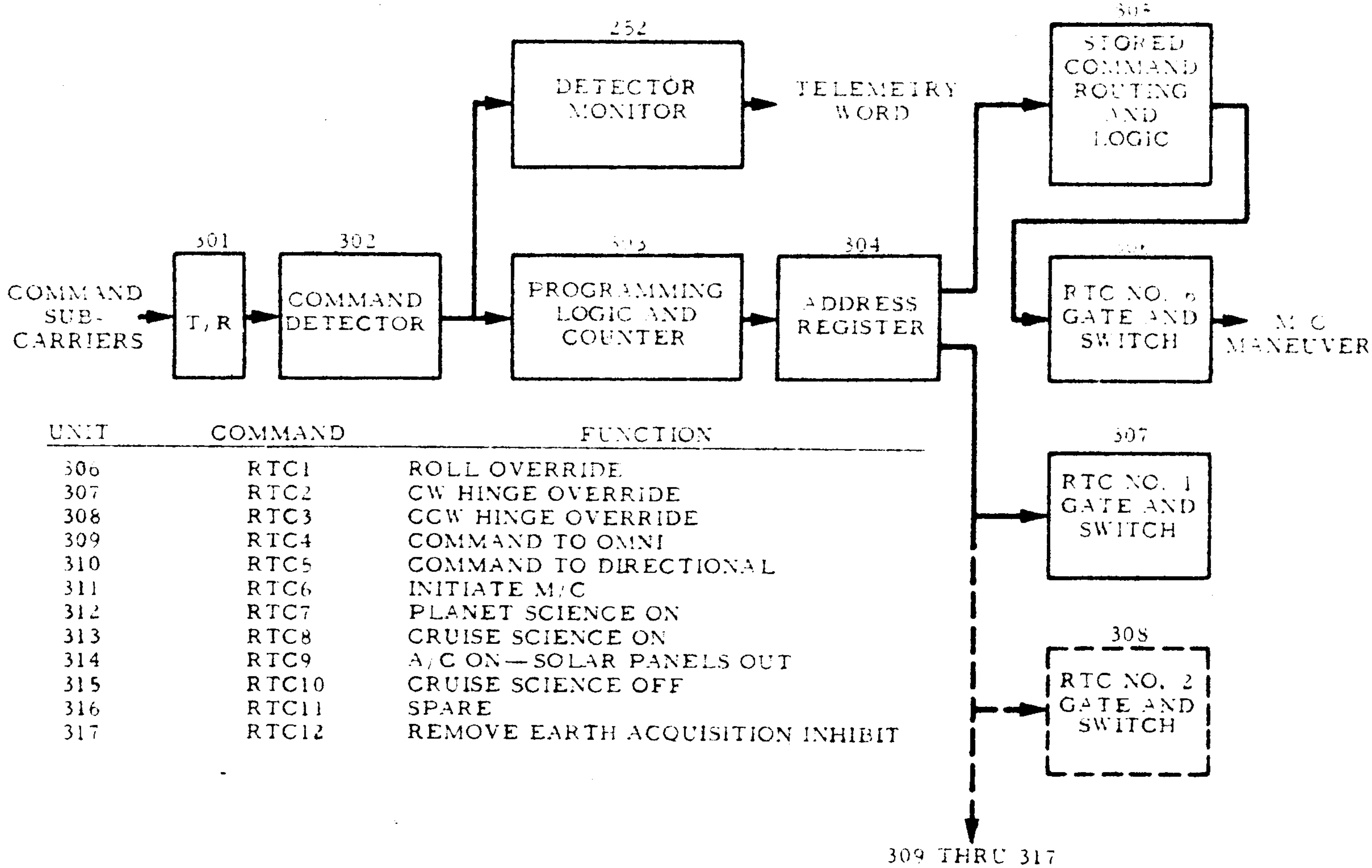
e. Units 251, 285, 286, 287, and 288

A failure of any of these units would shut down all data transmission from the spacecraft. It is conceivable, of course, that unmodulated subcarriers would be transmitted under some conditions; however, this mode of operation is not considered to add any value to the mission.

5. Ground Commands

The reliability block diagram for this function is depicted in Exhibit 5. As illustrated here, the function is restricted to the operations of command detection and decoding. The role of the transponder in receiving and demodulating the command subcarriers is not indicated. The first-order dependence upon the command power supply is shown by unit 301, and the next unit, 302, indicates the further dependence on the command detector. This latter unit involves considerable equipment; however, it appears that for successful command reception, all of this equipment must be operating with the exception of the detector monitor circuitry.

Units 303 and 304 were derived from the command decoder and include all of the equipment and circuitry required for the recognition of a command and the gating of the command to the proper channel. The stored commands are used for the midcourse maneuver, and the necessary routing and logic are shown in unit 305. Unit 306 introduces the real-time command which initiates the midcourse maneuver. All



UNIT	COMMAND	FUNCTION
306	RTC1	ROLL OVERRIDE
307	RTC2	CW HINGE OVERRIDE
308	RTC3	CCW HINGE OVERRIDE
309	RTC4	COMMAND TO OMNI
310	RTC5	COMMAND TO DIRECTIONAL
311	RTC6	INITIATE M/C
312	RTC7	PLANET SCIENCE ON
313	RTC8	CRUISE SCIENCE ON
314	RTC9	A/C ON—SOLAR PANELS OUT
315	RTC10	CRUISE SCIENCE OFF
316	RTC11	SPARE
317	RTC12	REMOVE EARTH ACQUISITION INHIBIT

EXHIBIT 5 - COMMAND DETECTION AND DECODING

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of the remaining units, 307 through 317, are individually associated with real-time commands and include only the equipment that can be identified with individual commands.

In assessing the effects of the failure of a unit within the command detection and decoding system, it is ultimately necessary to recognize the redundant role that is fulfilled by many of these commands. The brief listing of failure effects given below is concerned only with the loss of specific commands and not with the consequential effects of such losses on the spacecraft or on the mission.

a. Units 301, 302, 303, and 304

These units, comprising most of the command detection and decoding equipment, are required for the successful execution of any of the ground commands. A failure within any of these units will completely impair all of the ground commands.

b. Units 305 and 306

A loss of either of these units, should it occur prior to the midcourse maneuver, will prevent the successful completion of the maneuver.

c. Unit 307

This unit is associated with RTC 1, the roll override command. This command is required in the event of an acquisition of an incorrect target such as the moon rather than the earth. As such, the command is redundant to the probability that such an incorrect target will in fact not be acquired.

d. Units 308 and 309

These units are associated with RTC 2 and RTC 3, the hinge override commands. It is conceivable that these commands will be useful in a variety of circumstances; however, it is assumed for the purposes of this study they will serve only one function. In this function they are redundant to the antenna hinge update signal, and this in turn is required only in the event of a reacquisition following a non-catastrophic impact. A loss of either of these units is considered to be a loss of the redundancy.

e. Units 310 and 311

These units correspond to RTC 4 and RTC 5, the antenna change commands. As such, they are redundant to that portion of the attitude control which generates the signals for the antenna change. The study of the attitude control system revealed that the amount of equipment devoted solely to the origination of these signals is very small. Failures within the attitude control which cause a loss of the antennal change signals will generally also result in some type of impairment of the attitude control system. Accordingly, it was decided to ignore the apparent redundancy of the ground commands that are used to change the antennas and to consider these commands as an independent function that provides a measure of operational flexibility. A loss of these units removes the ground command capability but does not affect the normal mission.

f. Unit 312

This unit implements RTC 7, which turns on the planet science. This command is redundant to the CC and S function, which generates the encounter start signal. A loss of the unit negates this redundancy.

g. Units 313 and 315

These units are associated with RTC 8 and RTC 10, which command the cruise science on and off. Here again, the apparent redundancy of these commands is ignored for the purposes of this study. Cruise science is turned on by the attitude control when the earth gate indicates correct stabilization about the roll axis. In addition, the cruise science is turned off whenever the gyros are turned on. The quantity of hardware devoted to this implementation is not particularly significant, and it is assumed that the real value of these commands lies in the operational flexibility they provide. A loss of either unit would effectively destroy this capability.

h. Unit 314

This unit corresponds to RTC 9, the command that turns on the power for the attitude control and signals the pyrotechnics which permit the deployment of the solar panels. The command is clearly not intended for operational use throughout the mission, but rather as a backup for the very important CC and S signal which initiates these functions. A failure of the unit removes the redundancy.

i. Unit 316

This unit implements RTC 11, which is a spare command. The unit is not actually used in the assessment but has been included in the listing for completeness.

j. Unit 317

This unit serves a redundant function in providing the capability of RTC 12, the command that removes the earth acquisition inhibit. The removal of the earth acquisition inhibit as been programmed in the CC and S to occur one week after launch and again after the midcourse maneuver, and a failure of unit 317 would impair the ground command which is redundant to the generation of this signal.

6. Central Computer and Sequencer

The central computer and sequencer functions, as its name implies, to control the midcourse maneuver and as a sequencing clock for the various planned mission events. The hardware within this subsystem has been arranged into reliability blocks, and the interconnection of these blocks is depicted in Exhibit 6. The CC and S utilizes its own transformer rectifier, and its complete dependence upon this device is shown in unit 401. Clock functions are provided by an oscillator and a series of countdown circuits, some of which are common to all operations of the CC and S. This common circuitry together with the oscillator is shown as unit 402. All of the event timing functions are dependent upon additional countdown circuitry which is shown in unit 403. The implementation of this countdown is accomplished through the use of magnetic cores.

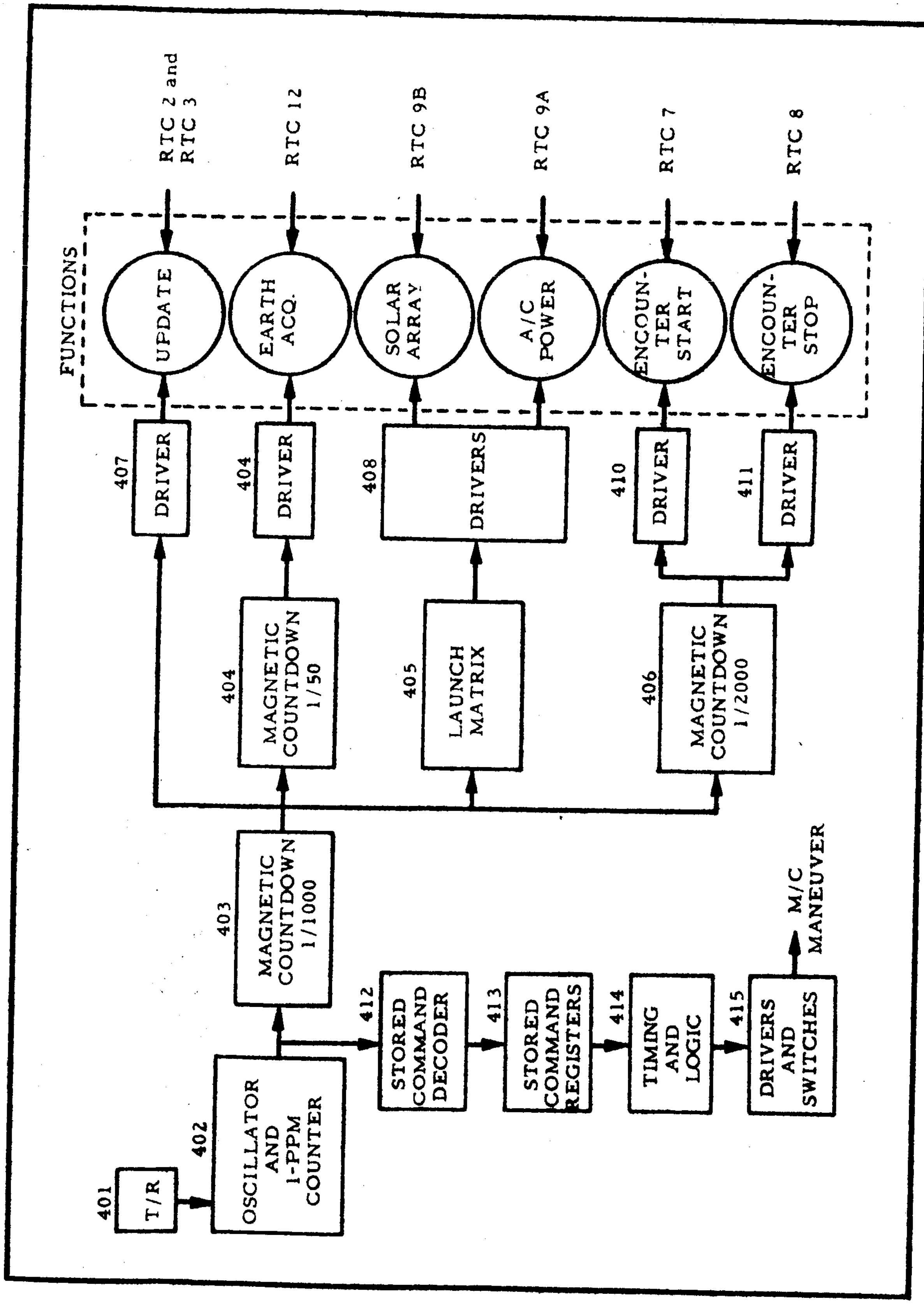

EXHIBIT 6 - CENTRAL COMPUTER AND SEQUENCER

Divider circuits constructed of magnetic cores make up part of unit 404, and the balance of this unit consists of a relay driver which removes the earth acquisition inhibit at the appropriate time. The signals to deploy the solar array and to energize the attitude control system are produced by the relay drivers, unit 408. These drivers are in turn actuated by the launch matrix, unit 405, which consists of logical circuitry to decode the appropriate states of the magnetic countdown unit 403. Unit 406 is a long-term countdown string, implemented by magnetic cores, which turns on the planet science at the beginning of the encounter phase. The signal is generated by a relay driver, unit 410, and the end of the encounter is signaled by a relay driver, unit 411.

The CC and S plays an important role in the correct execution of the midcourse maneuver. This is depicted by the string units 412 through 415, which are dependent only on the CC and S power supply, oscillator, and command countdown circuitry. The command decoder which was discussed previously does not decode the individual stored commands, but simply routes them to the CC and S. The decoding of these commands is accomplished within the CC and S by means of unit 412, which distinguishes between roll, pitch, and velocity commands and routes them to the appropriate storage registers. Dependence upon these registers is shown by the presence of the unit 413.

The sequence of events necessary for the midcourse maneuver is programmed into the CC and S, and the implementation of this sequential timing together with the necessary logic is included in unit 414. Finally, the drivers and switches which provide amplification of the midcourse maneuver commands are illustrated by the presence of unit 415. From the standpoint of reliability dependence, it is evident that units 412 through 415 could be combined.

The single-unit failure effects, which are reasonably obvious, are listed below.

a. Units 401 and 402

Failure of the power supply, oscillator, or common countdown circuitry will result in the loss of all CC and S functions.

The loss of a frequency reference for the spacecraft is considered to be catastrophic.

b. Unit 403

Any impairment of this sequence of dividers will cause the loss of all of the timing functions of the CC and S, but will not directly prevent the execution of the midcourse maneuver.

c. Unit 404

A failure of either the countdown circuitry or the driver will inhibit the earth acquisition function throughout the mission. The redundant ground command, RTC 12, will become the primary source of this signal in the event of a failure of unit 404.

d. Units 405 and 408

The launch matrix and associated drivers must operate in the early part of the mission to signal the deployment of the solar array and to energize the attitude control system. A redundant ground command is available in the event of a failure of these two units.

e. Units 406, 410 and 411

A loss of unit 410 or an impairment of unit 406 might deprive the mission of planet science unless the redundant ground command RTC 7 is available. Unit 411, which is responsible for returning the spacecraft to the cruise mode following the planet encounter period, is not considered in this assessment.

f. Unit 407

A failure of this driver would mean the loss of the update pulse and the consequent loss of the antenna hinge memory. In the event no reacquisitions are required during the cruise phase, this loss will not have any serious consequences. The redundant ground commands RTC 2 and RTC 3 are available as a backup for this update pulse.

g. Units 412, 413, 414, and 415

Any failure of these units will prevent the correct execution of the midcourse maneuver. If such a failure occurs after the midcourse maneuver, then nothing is lost.

7. Power Supply

The equipment for the power supply has been condensed into five reliability units, and the interrelationships of these units are shown in Exhibit 7. Prime power for the spacecraft is derived from a silicon cell solar array and from a silver zinc battery when there is no incident sunlight. These devices are shown as comprising unit 501; however, there is much corollary equipment included in this unit. For example, the battery charging components are considered to be a part of this unit.

Exhibit 8 shows the reliability blocks associated with the deployment of the solar array. It will be noted that there are two strings of pyrotechnic squibs, each of which can perform the unlatching function. It is necessary to remove a pin from each of six latches in order to begin the deployment operation. For each latch, the pin removal can be accomplished by one or the other of a pair of pyrotechnic squibs. The redundancy provided by this kind of arrangement is more than that which would exist for the simple parallel connection of two strings of squibs, and the mathematical formulation takes this into account. Following the unlatch operation, each of four hinges must support the solar array during the deployment period. Actuation power to erect the panels is furnished by two springs.

All of the equipment just described is included in unit 501; dc loads, consisting of pyrotechnic devices and attitude control valves, are supplied by the equipment that makes up unit 501. The booster regulator, unit 502, furnishes a constant 52-volt dc for inversion. This unit also includes most of the power synchronizer and much of the power switching and logic. The unit develops an isolated dc supply and adds its voltage in the correct proportion to the solar array voltage, thereby maintaining a fixed 52-volt dc output. Except for the battery loads, all electrical power on the spacecraft is dependent upon the booster regulator. Units 503, 504, and 505 designate the inverters which supply ac voltages at the correct frequencies for use throughout the spacecraft.

Spacecraft power is distributed primarily at 2.4 kc/s, and this is generated by unit 503. There is also need for 400-cps single-phase

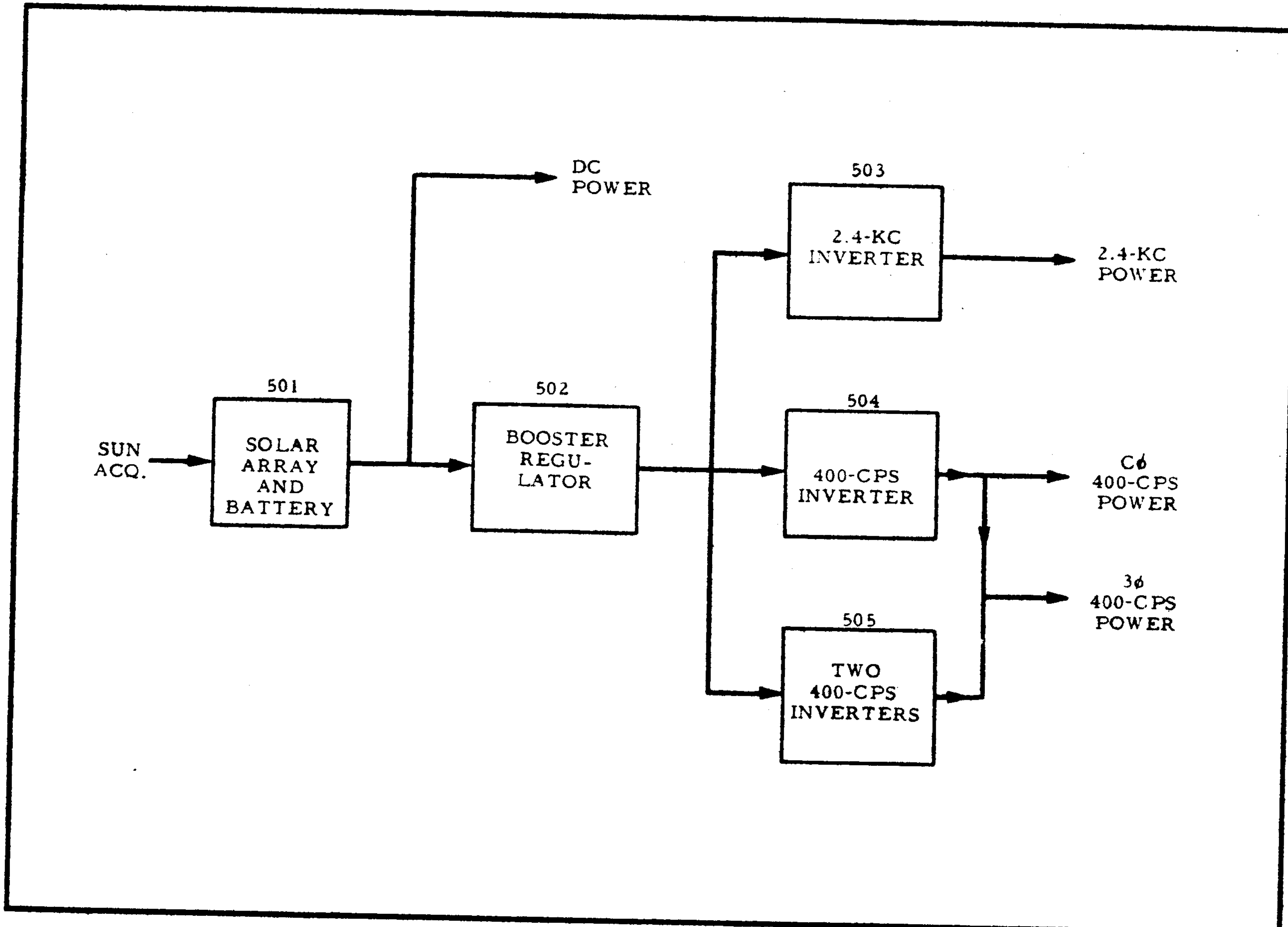

EXHIBIT 7 - POWER SUPPLY

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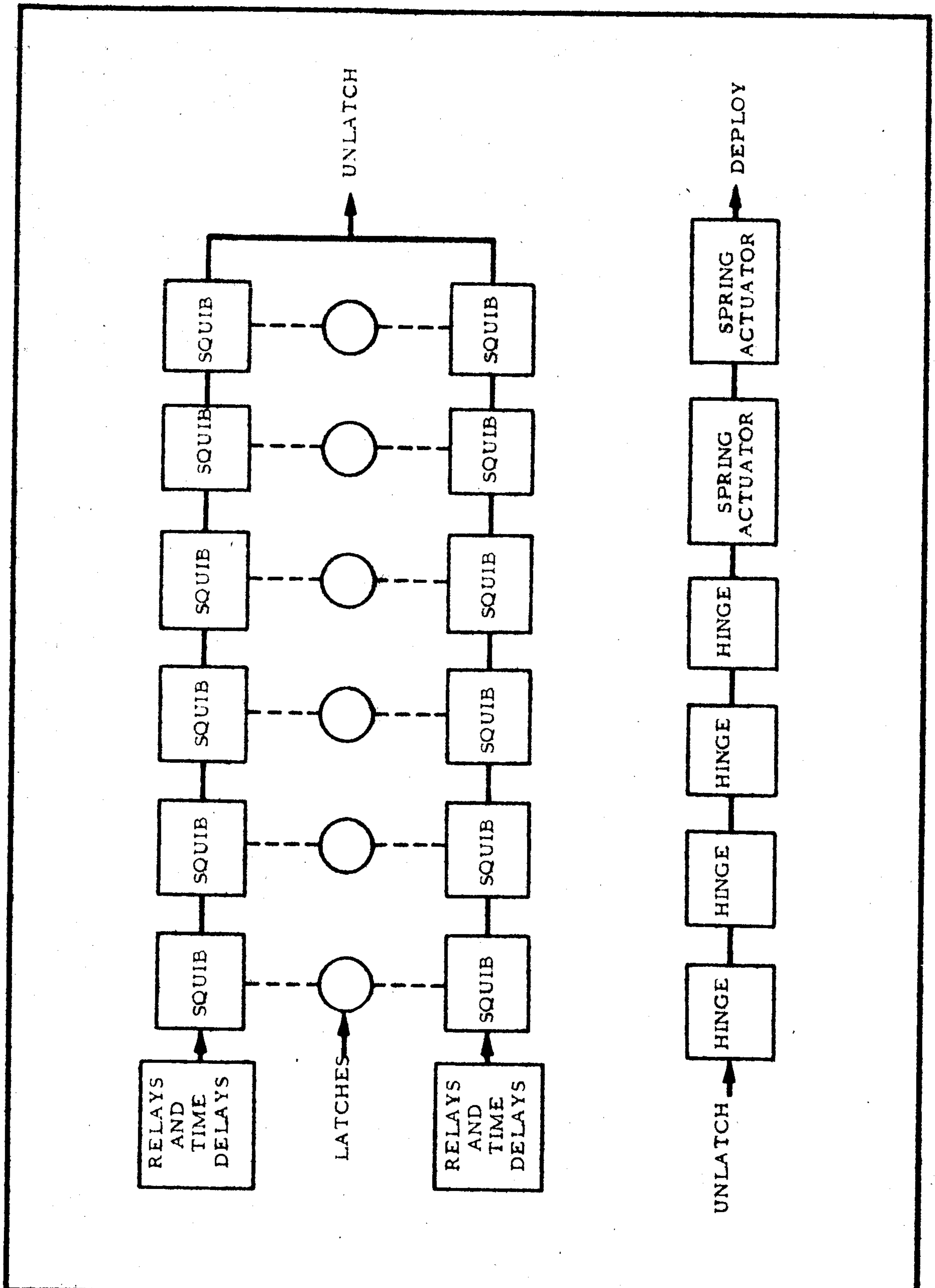

EXHIBIT 8 - SOLAR PANEL ERECTION

power as well as 400-cps three-phase power aboard the spacecraft. Three inverters are used to satisfy this 400-cps demand, and one of them, unit 504, also supplies the single-phase 400-cps demand. The remaining two inverters make up unit 505. It can be seen from the diagram that units 504 and 505 must work together to provide three-phase 400-cps power. However, only unit 504 need be operating to satisfy the 400-cps single-phase demand.

The effects of failure within the power supply are generally catastrophic as outlined below.

a. <u>Unit 501</u>

Loss of the prime power will shut down all operations on the spacecraft. It is, of course, true that a failure of the solar array due to, say, incorrect deployment will not result in an immediate shutdown. The battery is capable of maintaining the spacecraft operations for a period of time. Nevertheless, this is very short, and the consequences are considered to be catastrophic. The loss of the battery or battery charger might conceivably not affect the mission if it occurred after the last reacquisition; however, since unscheduled reacquisitions have been allowed for, it is necessary to assign first-order importance to the battery and its charger.

b. <u>Unit 502</u>

This unit assumes as much importance as the prime power generation, since it handles all spacecraft power with the exception of the direct battery loads. It is conceivable, of course, that it might supply dc power in a degraded form such as with the voltage out of tolerance. It is assumed for the purposes of this study that a failure of unit 502 will result in the loss of all spacecraft power.

c. <u>Unit 503</u>

The loss of this unit will shut down all spacecraft subsystems, because it deprives them of the 2.4-kc/s source which distributes power throughout the spacecraft. Admittedly, the 400-cps generation is not affected by a failure of unit 503; however, the availability of 400-cps power only is of little value under any circumstances.

d. Unit 504

The failure of this inverter reduces the three-phase generation of 400-cps power to two-phase, and this is considered unsuitable for use with the gyros. The antenna hinge servo and radiometric scan would also be impaired by a loss of this inverter.

e. Unit 505

A failure of either of the inverters that make up this unit would cause the loss of the three-phase 400-cps power and a consequent shutdown of any of the functions that require the gyros. The single-phase devices such as the antenna hinge servo would not be affected by this type of failure.

8. Attitude Control

The coasting attitude control system has been simplified to a series of block diagrams as depicted in Exhibits 9 and 10. The first of these illustrations indicates the reliability units that are required for successful sun acquisition. The primary and secondary sun sensors and the sun gate are introduced by unit 601. The sun gate is included because a large number of functions depend upon the output signals of this device. The pitch and yaw gyros and associated electronics are identified as unit 602. These units, which are shut down normally, serve to provide rate feedback during the acquisition cycle. Acquisition with the derived rate feedback around the switching amplifiers is theoretically possible; however, it is assumed that without the gyros a stable limit cycle cannot be reached.

Unit 603 serves to group a number of relays that provide important switching functions and also the variety of small but important power supplies contained within the attitude control system. The actuation of the attitude control system is effected through cold gas expulsion nozzles which are controlled by amplifier-actuated valves. Equipment of this type associated with the pitch and yaw axis control is

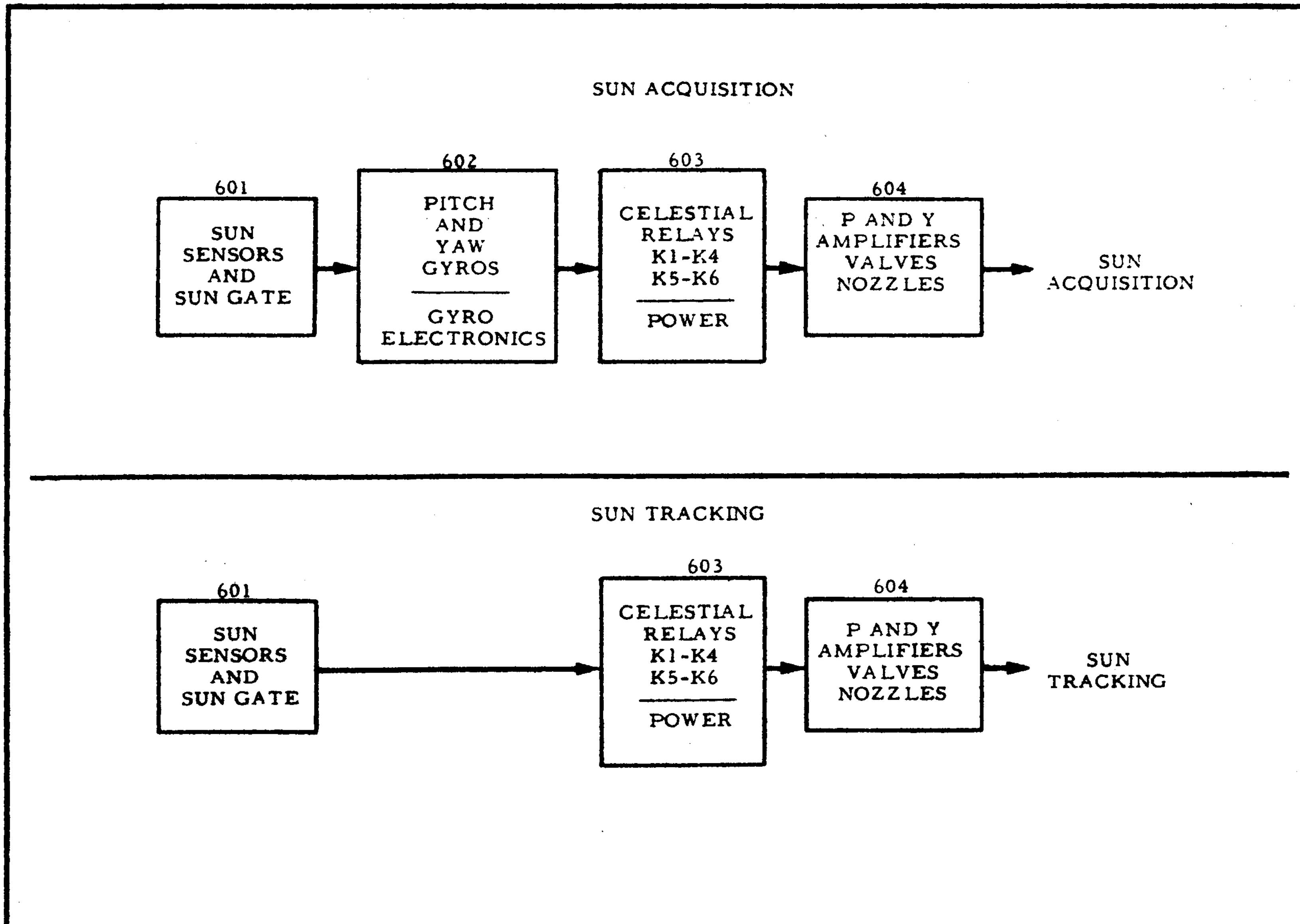

EXHIBIT 9 - SUN ACQUISITION AND TRACKING

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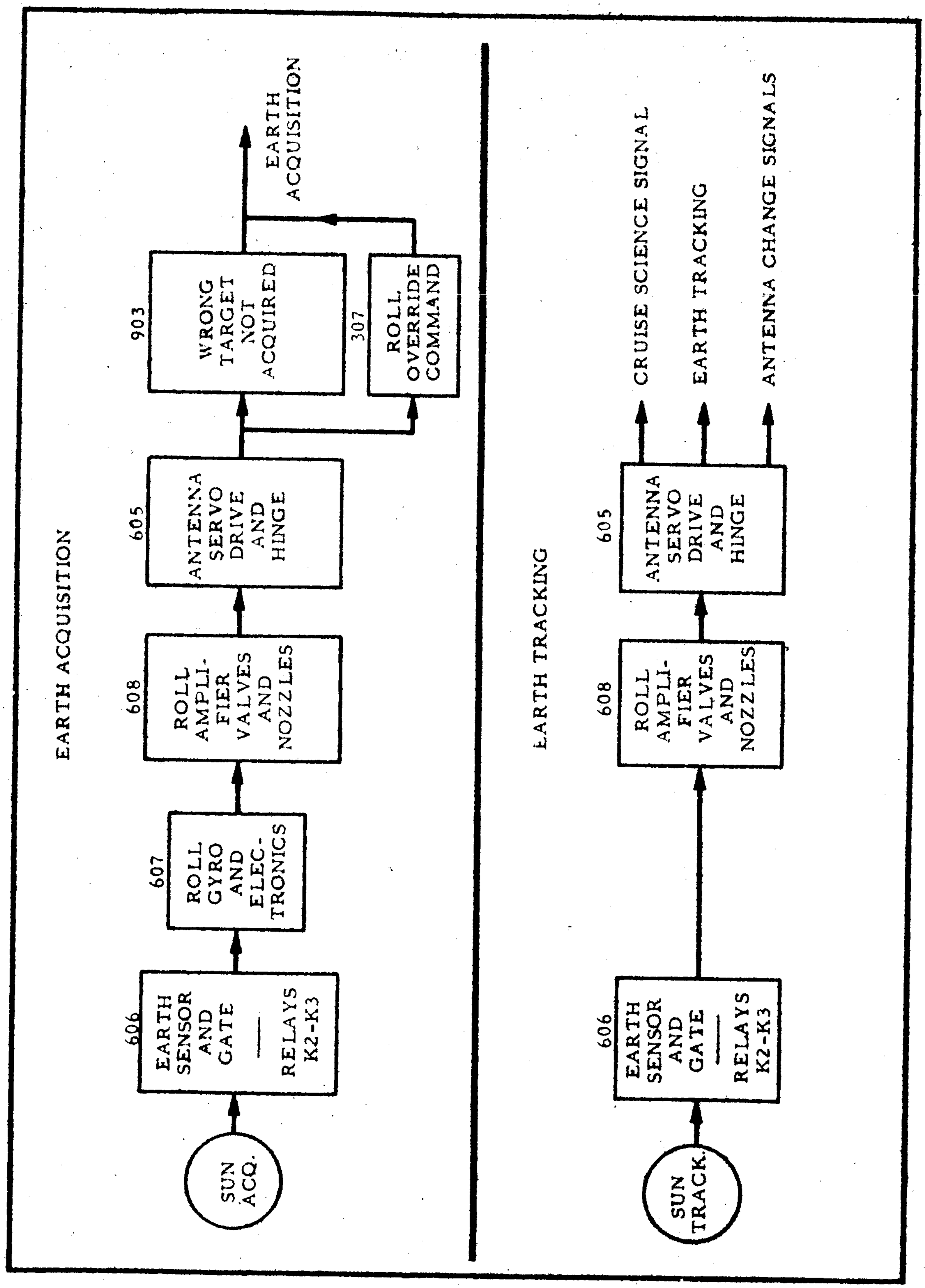

EXHIBIT 10 - EARTH ACQUISITION AND TRACKING

grouped in unit 604. All units are shown in line, there being no operational redundancy and only one functional output.

Once the sun has been acquired, the task of tracking it is accomplished by means of these same units with the exception of unit 602, the gyros. These are de-energized following acquisition, and derived rate feedback is used for stabilization. Exhibit 10, which illustrates the reliability units needed for earth acquisition and tracking, shows that this function is dependent upon the acquisition of the sun. The electronics for the long-range earth sensor and earth gate are shown in unit 606, and additional earth gate relays are also included within this unit. Unit 607 introduces the roll gyro and its associated electronics, since these are required during the earth acquisition cycle for rate feedback. The actuation devices for roll axis rotation and the roll amplifier that drives them are shown in unit 608.

A distinctive part of the earth acquisition equipment is the directional antenna. The degree of freedom afforded by this movable antenna is servo-controlled by the earth sensor output. Unit 605 combines the mechanical actuation hardware for the antenna servo drive including the servo motor, associated gearing, and the antenna hinge. This unit also accounts for the electronics, such as the servo amplifier, which control the operation of the drive. This unit has been related to the attitude control system because it serves a more basic function as part of this subsystem than as part of the transponder.

Unit 903 is not a hardware unit, but represents a first-order estimate of the probability that the moon has not been acquired erroneously. In the event of a failure of this unit (i.e., the moon has in fact been acquired), the roll override command, unit 307, can function to break the lock and initiate a reacquisition. As was the case with sun tracking, the earth lock can be maintained without the roll gyro, unit 607, since derived rate feedback will provide the necessary limit cycle stability. The complement of units required for earth tracking is illustrated in Exhibit 10, and it can be seen that the roll gyro has been eliminated. It should be noted that sun tracking is a prerequisite for successful earth tracking.

A recital of unit failure effects is unnecessary for this subsystem, because it can be seen that all units are "in line," and any unit failure will have catastrophic results with respect to the associated tracking function. As just indicated, a failure of any sun tracking unit will cause the loss of both the sun tracking and earth tracking functions. It is assumed that the converse is not true, and that the failure of an earth tracking unit will affect the earth tracking function only. This ignores certain coupling modes that may exist, such as the possibility that a leaky valve could reduce the gas pressure on the entire system. The fact that the gyros are operated only during the acquisition cycle is significant inasmuch as these devices have inherently high failure rates, and sustained operation of them would reduce the reliability of the attitude control subsystem.

There is some possibility that a noncatastrophic impact during the cruise phase will upset the attitude control stability and automatically reinstitute the acquisition cycle. For this reason it is necessary that the gyros remain operable, though de-energized, throughout the mission. This possibility of a noncatastrophic impact has been introduced in the form of unit 902, which is shown in Exhibit 11. It will be observed that the gyros are shown as redundant to the probability that no impact will occur.

9. Midcourse Maneuver

The accomplishment of the midcourse maneuver is effected by means of several units that have been assigned to other subsystems. Notable among these are certain attitude control units, and this direct dependence is indicated in Exhibit 12, which also shows three units that are assigned solely to the midcourse maneuver function. Unit 701 includes the gyro capacitors and the relays that switch the gyros to the position mode. This unit includes also the accelerometer and associated electronics which serve the function of measuring the velocity increment. Unit 701 operates throughout the midcourse maneuver.

Jet vane control of the spacecraft attitude during the powered phase of the mission is accomplished by means of an autopilot, and

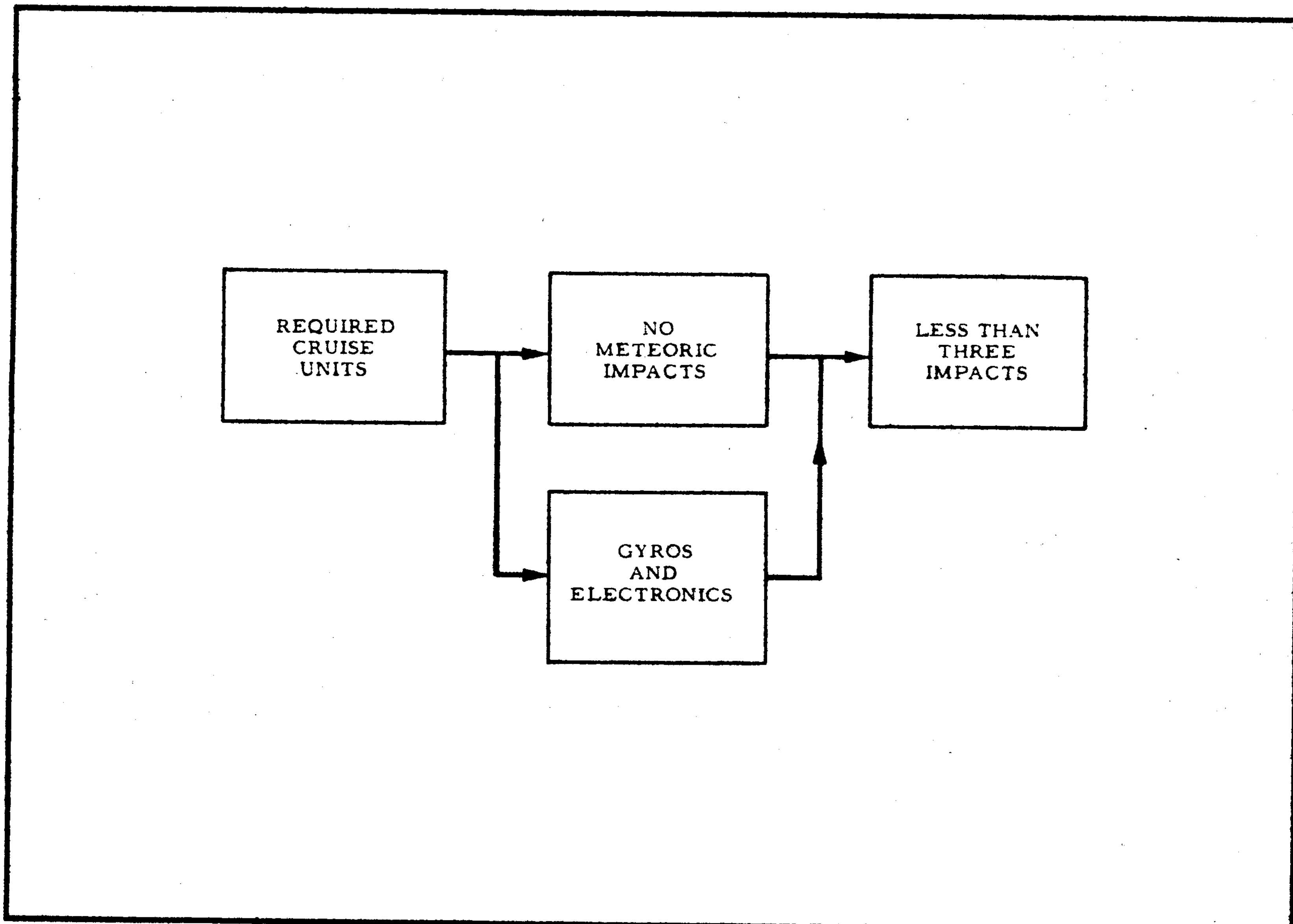

EXHIBIT 11 - CRUISE REACQUISITION

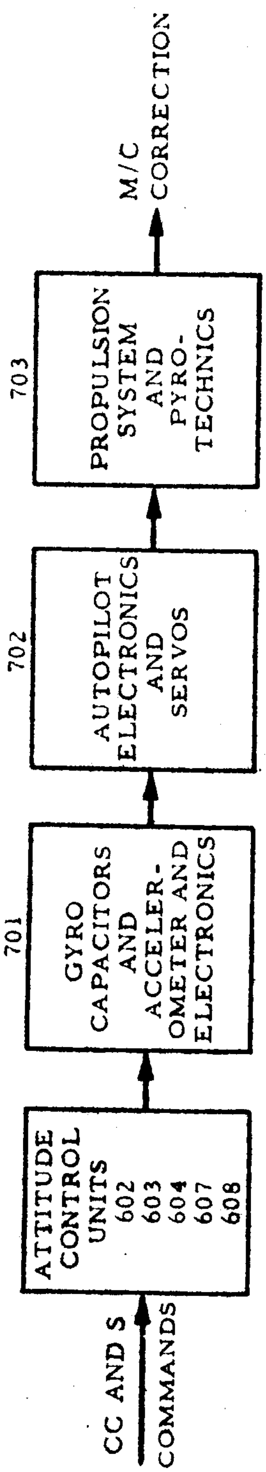

EXHIBIT 12 - MIDCOURSE MANEUVER

this device together with th va e servos is assigned to unit 702. The propulsion system wit 03 includes the pyrotechnics and valves which control the fl hydrazene propellent, the oxidizer, and the pressurized nitrogen. These units function only during maneuver and are not required after that time.

As with the attitude control subsystem, the effects of a unit failure are straightforward, and it can be seen that such a failure would result in the loss of the maneuver or in an incorrect maneuver.

10. Transponder

The transponder, which completes the communications loop between the spacecraft and the DSIF, is shown in reliability block diagram format in Exhibit 13. As indicated in the exhibit, the transponder performs three functions--tracking, command reception, and data transmission. Unit 804, shown at the left of the diagram, represents the phase modulation equipment which impresses the data subcarriers on the transmitted carrier. Normally, this carrier is developed in unit 803, the phase-locked receiver, by means of a VCO which is driven into coherence with a received carrier. Unit 803 includes not only the VCO and its associated control loop but also an AGC loop and the necessary i-f strips. The phase-locked loop within unit 803 also serves to demodulate the commands. In the event the AGC loop indicates the loss of the received carrier or the failure of the VCO to track it, the bias is removed from a standby crystal oscillator, shown as unit 805. The solid-state switching which removes the bias is identified as unit 806. These units provide the transmitted carrier in the event of a malfunction within unit 803, and consequently are shown as redundant to this unit, but only for the purpose of transmitting data and one-way tracking.

All functions of the transponder are wholly dependent upon unit 802, which is the transponder power supply or transformer-rectifier. Similarly, there is total dependence on unit 807, which is comprised of the frequency multipliers and transmitter cavity driver. Two microwave cavities are available for transmitter power, and these are switched by means of a relay which energizes one or the other filament, as appropriate.

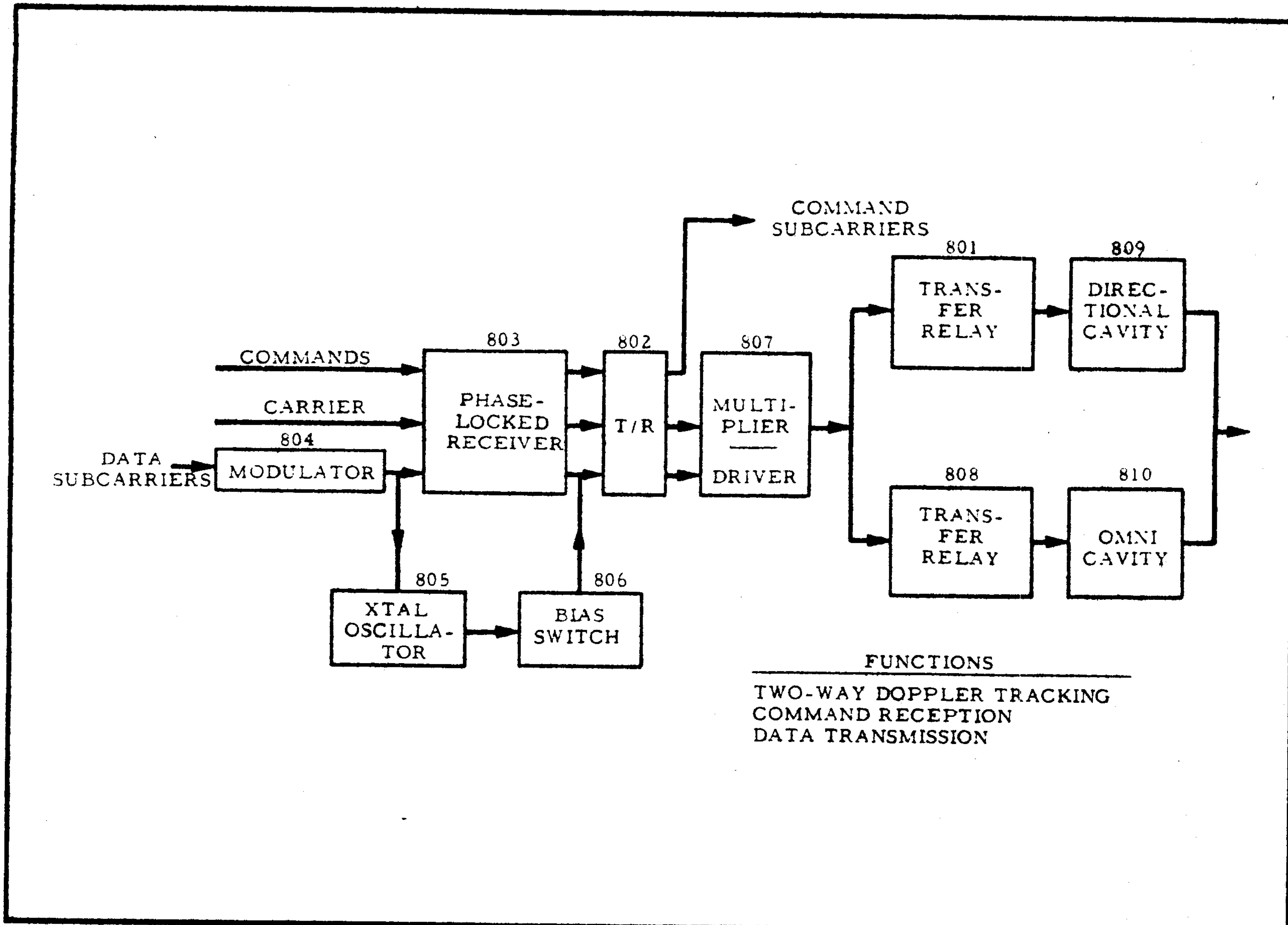

EXHIBIT 13 - TRANSPONDER

Reliability-wise, the transfer relay is shown in both units 801 and 808 in an effort to account for both possible failure modes of this relay. Unit 809 is the cavity that supplies the directional antenna, and unit 810 is the cavity that supplies the omnidirectional antenna. Although these units are shown in parallel, their redundancy is a function of the operational situation. The directional cavity can be used only when the earth has been acquired, and the omni cavity lacks sufficient power to provide adequate transmission beyond approximately the 42nd day of the mission.

The effects of unit failures may not be entirely clear from this exhibit, and it is worthwhile to review them.

a. Unit 804

If the modulator fails, neither engineering nor science data can be transmitted. The tracking and command reception functions of the transponder would not be affected by this failure.

b. Unit 803

The loss of the phase-locked receiver would have multiple effects. The auxiliary oscillator would be switched on, and data transmission would be accomplished by means of this noncoherent carrier source. Two-way doppler tracking would be lost, and any tracking of the vehicle would have to be achieved by means of one-way tracking of the noncoherent crystal oscillator. No commands could be received, since there would be no capability for demodulating them.

c. Units 805 and 806

A loss of these units would not affect the normal mission inasmuch as they serve in a standby capacity. The redundancy they provide would be negated.

d. Unit 802

It is clear that the failure of the transformer-rectifier would result in the loss of all transponder functions.

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e. Unit 807

The loss of this unit implies the inability to transmit from the spacecraft. The tracking and data transmission functions would be lost. It would still be possible to receive commands; however, there would be no indication of the successful receipt or execution of any command because of the loss of the transmission capability.

f. Units 801 and 808

Two failure modes of the transfer relay are accounted for by these units, and the failure effects would depend upon the point in the mission at which the failure occurred. The loss of either unit is equivalent to the loss of the associated cavity.

g. Unit 809

Impairment of the directional cavity would be catastrophic, as far as communications are concerned, any time after approximately the 42nd day of the mission. This cavity provides the only means of transmitting from the spacecraft at the longer distances.

h. Unit 810

The cavity supplying the omnidirectional antenna is required during the early phases of the mission. Without it, engineering data transmission and the vehicle tracking function would be lost during the first week, and this would be likely to have serious consequences. In the event of a successful earth acquisition, communications would be reestablished by means of the directional antenna; however, the transponder would again fail to function during the midcourse maneuver.

11. Thermal Control

The electronic assembly that includes the attitude control subsystem and the central computer and sequencer is equipped with an active thermal control system. This system, consisting of eight bimetal actuated louvers, is subject to failure through a loss of an actuator on the louver support bearings. No detailed study of the thermal control system was possible; however, calculations derived from JPL

Space Program Summary 37-9 indicate that the following failure effects can be expected:

	Failure State	Failure Effect
a.	One louver fails shut:	$122^{\circ}F$ assembly temperature
b.	Two louvers fail shut:	$141^{\circ}F$ assembly temperature
c.	One louver fails open:	$-4^{\circ}F$ assembly temperature
d.	Two louvers fail open:	$-45^{\circ}F$ assembly temperature

In consideration of these possibilities, a failure of the active thermal control system has been defined as the failure of at least two louvers in the open or closed position. To introduce this failure mode into the assessment unit 901 has been contrived. The calculations for the failure rate of this unit are given in Appendix A. The passive thermal control system has not been assessed in this study, and its reliability has been assumed to be unity.

IV. SPACECRAFT RELIABILITY

The determination of system reliability is based upon the engineering breakdown or unit selection which was described in Section III. In order to supply an adequate background for an understanding of the numerical evaluation which will be given in this section, several important steps in the reliability analysis are detailed initially. Failure-rate assignments are discussed and are then delineated both for component parts and for reliability units. The configuration of the unit complement is presented for the normal mission. The specialized mathematical model used in this assessment is treated next, and it will be recognized that this follows the form of the generalized model developed[1] for the Mariner spacecraft. The mission value apportionment schedule prepared by the Systems Design Section of Jet Propulsion Laboratory is introduced to complete the setting for the numerical evaluation. Finally, the detailed reliability calculations and results are given for both the classical approach and the figure-of-merit method.

A. Failure Rates for Components and Units

1. Assumptions Regarding Failure Rates

For each of the 97 reliability units considered in this assessment, a failure rate was determined on the basis of an enumeration of components within the unit, together with a failure-rate estimate for each type of component. Many sources were reviewed for component failure rates, and a final selection was made of six sources for the rates used in this study. A detailed discussion of PRC's position concerning failure rates is given in Appendix B. Special emphasis is placed therein on four high-population component parts; viz, capacitors, resistors, diodes, and transistors.

In making the selection of data sources, the applicability of all possible sources was weighed. The most important problem to be

[1] Mariner R Reliability Model Formulation and Qualitative Assessment (PRC R-266), 24 August 1962.

resolved in making decisions of this nature is that of equating space environmental severity to some earth environment on which operational data is available. Based on the work done both on previous projects and on this study, the assumption was made that the severity of space environment is equivalent to that experienced by ground support equipment. This is a compromise between "benign" environments (e.g., no vibration) and "active" environments. The fact that space environment failure data does not exist in adequate quantity is, of course, considered a difficulty in the assessment of the reliability of any spacecraft. To the extent that finality in failure-rate determination cannot be achieved, it can be stated that the failure rates used in this assessment are believed to be generally conservative.

In a few cases the failure rates of some mechanical components were lowered from that of the data source by a factor determined by engineering judgment. This was done because the mode of operation of these components in Mariner R is much less stringent after injection than their pre-injection operating mode.

For two low-population electronic parts, varicaps and photo multiplier tubes, no data were available; the rates used are estimates based on comparable equipment. Available failure rate data on solar cells indicate that, excluding degradation effects, catastrophic failure of cells within the array is not significant during a mission time of four months. Degrading effects of particle bombardment and similar phenomena are not known for a deep space environment; hence, a zero failure rate has been postulated for the solar cells and panels.

No failure rate estimates for magnetic cores (or transfluxors) could be located. Conversations with personnel responsible for maintainence of computer equipment have led to an assignment of zero failure rate for this part. Thermal control louvers have established failure rates, but these are based on the stresses of the launch phase. Accordingly, a zero failure rate has been used in this study for louvers, inasmuch as only the brief period of thrust during the maneuver could affect them.

Another assumption made in the determination of the failure-rate estimates has been that all components (without exception) have been applied at 25 percent of their rated operating loads. Also, the assumption was made that all components (without exception) operate in an ambient environment of 35° C.

A final assumption concerns the failure rate of the "one-shot" units, (e.g., units 602 and 607, containing the three gyros and their associated electronics; units 702 and 703, associated with the midcourse maneuver; and some command units). For each of these units, the failure rate was estimated for an hour's continuous operation. These units enter into the computational equations for just one hour, regardless of the length of the portion of the mission under consideration. For example, the probability of successfully performing the midcourse maneuver requires, among other conditions, that units 701 and 703 (both "one-shot" units) operate successfully for one hour only. There is little published evidence regarding the effect on the failure rate of equipment that is turned on, off, and then on again in earth environments;[1] even less is available for space environments. It is believed that the one-hour requirement is a fair assumption concerning such equipment on a mission whose total time is long compared with the assumed operating period.

2. Component Failure Rates

As already indicated, it is considered that component failure rates used on this study are conservative in magnitude due to the unknown effects of the several assumptions which have been enumerated. These component failure rates are tabulated and identified by source in Exhibit 14. The six sources from which the failure rates in Exhibit 14 were obtained are as follows:

Source 1: Reliability Stress Analysis for Electronics Equipment, Proposed MIL Handbook 217 (WEPS), 31 December 1961

Source 2: Minuteman Parts Reliability, Autonetics Report No. EM-2496-3

[1] ARINC study of shipboard equipment (Satellite Reliability Spectrum, 173-5-280).

Source 3: Reliability Application and Analysis Guide, M160-54 (Rev. 1), The Martin Company, July 1961

Source 4: Compilation and Analysis of Reliability Data on Selected Flight Control Components, PRC R-235, Planning Research Corporation, Confidential, December 1961

Source 5: Reliability Application and Analysis Guide, Avco Corporation, April 1962

Source 6: Reliability Analysis Data for Systems and Component Design Engineers, TRA-873-74, General Electric, September 1961

3. Unit Failure Rates

The total number of components used in this study for each of the reliability units is given in Exhibit 15. Also shown is the failure rate, λ , for each unit. Appendix A provides additional detail on how these unit rates were determined from component failure rate estimates and gives a component count for each unit.

B. Unit Configuration for the Normal Mission

The normal mission, as defined in this assessment of the Mariner R, demands that all reliability units operate successfully as required from the time of injection until the encounter phase is terminated. The total length of the mission is assumed to be 2590 hours, but the operating time requirement for individual units varies according to specific events within the mission period. This section discusses the configuration of the unit complement during these events.

For reliability purposes, each unit is considered to be at any given time in one of four operating situations: (1) energized but not fulfilling a specific function, (2) energized and functioning or operating, (3) not needed, and (4) needed in a redundant capacity. Exhibit 16 tabulates the reliability units in terms of these situations by critical events within the mission.

During the first half hour after injection, most units are energized. The cruise science units are "not needed," since their contribution to the figure-of-merit begins at the end of the midcourse maneuver and continues

EXHIBIT 14 - ESTIMATES OF COMPONENT FAILURE RATES

Item	Failure Rate, $\lambda \times 10^{-6}$	Source
Accelerometer	28.00 hours	3
Actuators, bimetallic	.40 hour	3
Actuators, spring	1.05 actuations	3
Battery cells	.75 hour	6
Bearings	5.00 hours	5
Bearings, ball	9.00 hours	5
Bearings, sleeve-type	.40 hour	3
Cadmium sulfide cells	.38 hour	6
Capacitors, ceramic	.01 hour	1
Capacitors, glass	.01 hour	1
Capacitors, mica	.01 hour	1
Capacitors, paper	.01 hour	1
Capacitors, tantalum, solid	.08 hour	1
Cavities	.20 hour	6
Chokes	.20 hour	3
Clutch	3.00 hours	5
Cores	.00 hour	-
Crystals	1.00 hour	3
Diodes, power	.01 hour	1
Diodes, silicon	.15 hour	1
Diodes, zener	.26 hour	2
Engine, rocket, thrust chamber	2.00 cycles	6
Gears	1.20 hours	5
Gears, helical	.50 hour	5
Gears, compound	6.30 hours	5
Gears, anti-backlash	9.00 hours	5
Gears, spur	6.30 hours	4
Hinge	.02 actuations	3
Jet vane	.00 hour	-

EXHIBIT 14 (Continued)

Item	Failure Rate, $\lambda \times 10^{-6}$	Source
Joint, rotary coaxial	75.00 hours	5
Inductors	.20 hour	3
Klystron	10.00 hours	6
Latch	.02 actuations	3
Louvers	.00 hour	-
Motor with gear and brake	16.00 hours	5
Photo multiplier tube	3.80 hours	6(1)
Pinion	1.20 hours	5
Potentiometer	1.08 hours	3
Rate gyros	294.00 hours	4
Rectifiers	1.20 hours	3
Regulator, nitrogen	4.40 cycles	6
Relays (1 actuation per hour or less)	.60 hour	3
Resistors, compositon	.01 hour	1
Resistors, film, signal	.23 hour	1
Resistors, film, power	1.08 hours	1
Resistors, wirewound, accurate	1.03 hours	1
Resistors, wirewound, power	.22 hour	1
Servo motors	15.00 hours	5
Solar panel	(see text)	
Squibs	106.00 actuations	4
Tank and bladder, propellant	200.00 cycles	6
Transformer	2.00 hours	3
Transistors	.30 hour	1
Thermistor	.30 hour	1
Torque motors	15.00 hours	5
Valve, ignition cartridge	106.00 actuations	6
Valve, nitrogen	106.00 actuations	6

EXHIBIT 14 (Continued)

Item	Failure Rate, $\lambda \times 10^{-6}$	Source
Valve, propellant, start	106.00 actuations	6
Valve, propellant, shutoff	106.00 actuations	6
Valves and nozzles	.18 hour	4
Varicap	.30 hour	1(2)
Wormshaft	4.00 hours	5

Notes: (1) Failure rate assumed 10 times that of cadium sulfide cells.
(2) Failure rate assumed equal to that of transistors.

EXHIBIT 15 - UNIT FAILURE RATES

Unit	Name	Number of Components	Failure Rate, $\lambda \times 10^{-6}$/hour
Science Measurements:			
101	Relays	6	2.25
102	Scan logic and relays	316	30.71
103	Relays	7	3.30
104	D-D converter	733	80.22
105	A-D converter	388	44.21
106	Shift register, P/N generator, buffer	473	44.52
107	Timer and subframer	616	61.56
108	200-hour check, relays	232	22.52
109	Science T/R	111	13.07
Medium- and Low-Rate Engineering Data:			
201A-C	L/L switch	18(1)	3.18(1)
202A-F	C switch	10	2.81
203A-J	L/L switch	18	3.18
204A-I	L/L switch	18	3.18
205A-I	D switch	17	3.17
206	Low-deck programmer	374	104.54
207	L/L	72	13.48
208	C programmer	259	16.32
242A	A1 switch	10	2.81
Engineering Data:			
241A-I	Isolated power supply	13	5.55
242B-J	A or B deck switch, 9 high-rate words	10	2.81
242K-R	A or B deck switch, 7 high-rate words	10	2.81
243	A-D converter	528	47.05

Note: (1) Number of components and failure rate shown are for each one of the multiple units.

EXHIBIT 15 (Continued)

Unit	Name	Number of Components	Failure Rate $\lambda \times 10^{-6}$/hour
Engineering Data (continued):			
244	Event register No. 1	104	9.69
245	Event register No. 2	104	9.69
246	Event register No. 3	97	7.63
247	Event register No. 4	106	18.43
248	Event sequencer	41	3.40
249	Transfer register	384	26.98
250	BO F/F	15	1.01
252	Command monitor	287	78.01
Subcarrier Generation and Modulation:			
251	T/R	106	27.18
280	Mode logic and transfer, engineering	22	3.00
281	Mode logic and transfer, science	22	3.20
282	Data modulator	45	3.62
283	Master counter, decks A/B programmer, 24-word timer	1282	92.61
284	Sync modulator	25	2.25
285	Mixer	7	1.50
286	Subcarrier generation	100	7.05
287	P/N generator	157	15.42
288	Isolated amplifier	6	.64
Command Detection and Decoding:			
301	T/R	18	4.82
302	Command detector	607	71.32
303	Programmer logic and counter	275	30.55
304	Address register	180	18.24
305	S.C. routing logic	81	16.11
306	RTC No. 6 gate and switch (initiate M/C)	20	4.58

EXHIBIT 15 (Continued)

Unit	Name	Number of Components	Failure Rate, $\lambda \times 10^{-6}$/hour
Command Detection and Decoding (continued):			
307	RTC No. 1 gate and switch (roll override)	20	4.58
308	RTC No. 2 gate and switch (CW hinge override)	20	4.58
309	RTC No. 3 gate and switch (CCW hinger override)	20	4.58
310	RTC No. 4 gate and switch (command to omni)	20	4.58
311	RTC No. 5 gate and switch (command to directional)	20	4.58
312	RTC No. 7 gate and switch (planet science on)	20	4.58
313	RTC No. 8 gate and switch (cruise science on)	20	4.58
314	RTC No. 9 gate and switch (A/C on--solar panels out)	20	4.58
315	RTC No. 10 gate and switch (cruise science off)	20	4.58
316	RTC No. 11 gate and switch (spare)	19	4.69
317	RTC No. 12 gate and switch (remove earth acquisition inhibit)	20	4.58
Central Computer and Sequencer:			
401	T/R	30	6.45
402	Oscillator and 1-ppm counter	401	74.28
403	Magnetic countdown, 1/1000	81	13.02
404	Magnetic countdown, 1/50	72	12.64
405	Launch matrix	61	10.15
406	Magnetic countdown, 1/2000	100	16.30
407	Driver	17	3.65
408	Driver	16	3.57

EXHIBIT 15 (Continued)

Unit	Name	Number of Components	Failure Rate, $\lambda \times 10^{-6}$/hour
Central Computer and Sequencer (continued):			
409	Driver	16	3.57
410	Driver	17	3.66
411	Driver	22	4.13
412	S. C. decoder	315	61.31
413	S. C. registers	540	84.86
414	Timing and logic	171	29.98
415	Drivers and switches	175	35.01
Power Supply:			
501	Solar array and battery Probability of solar panel deployment: .999397	120	37.70
502	Booster regulator	157	31.16
503	2.4-kc inverter	16	11.06
504	One 400-cps inverter	90	20.67
505	Two 400-cps inverters	56	24.99
Sun Acquisition and Tracking:			
601	Sun sensors and gate	16	3.49
602	Pitch and yaw gyros, gyro electronics	145	611.86
603	Celestial relays	37	11.80
604	Pitch and yaw amplifiers, valves, and nozzles	114	23.28
Earth Acquisition and Tracking:			
605	Antenna servo and hinge	137	299.38
606	Earth sensor and gate	491	85.88
607	Roll gyro, gyro electronics	49	302.23
608	Roll amplifier, valves, and nozzles	84	8.33

EXHIBIT 15 (Continued)

Unit	Name	Number of Components	Failure Rate, $\lambda \times 10^{-6}$/hour
Midcourse Maneuver:			
701	Gyro capacitors, accelerometer, electronics	182	57.93
702	Autopilot electronics and servos	134	113.89
703	Propulsion system Reliability of deployment pyrotechnics: .9999	32	690.40
Transponder:			
801	Transfer relays	10	1.67
802	T/R	81	10.70
803	Phase-locked receiver	568	91.12
804	Modulator	13	1.04
805	XTAL oscillator	17	2.99
806	Bias switch	13	.71
807	Multiplier, driver	117	25.61
808	Transfer relays	10	1.67
809	Directional cavity	10	10.85
810	Omni cavity	10	10.85
Thermal Control:			
901	Thermal control	36	17.0

through encounter. During the time immediately after injection, there are three units involved in a redundant capacity. Unit 314, comprising RTC-9 gate and switch, and those units of the CC and S which receive this command are needed as back-up to insure that the attitude control is placed in operation and the solar panels are deployed.

Sun acquisition is accomplished during the next 30 minutes. All the engineering data units are required to be functioning in this interval, by definition of the normal mission. The sun could be acquired with some of the units down, but this is not a normal route. The power supply and attitude control units associated with sun acquisition must be operational, as well as certain units in command, CC and S, and transponder. It should be noted here that in this study there is no difference in the unit failure-rate estimate for the (1) energized or (2) operational conditions. For example, in computing the probability that the earth tracking units successfully complete the earth acquisition event, the same failure-rate estimate is applied for the 167 hours that have elapsed since injection as is applied during acquisition.

The next interesting event is the earth acquisition, requiring 30 minutes and occurring 167 hours after injection. Both the earth acquisition and sun acquisition require "one-shot" units, the gyros. The assumption made in the determination of failure-rate estimates for "one-shot" units should be recalled; viz, these devices enter the probability equations for one hour, regardless of the length of the event under consideration. Exhibit 16 designates the "one-shot" units used in the study as "non-time-dependent."

There are two units, 902 and 903, that are not hardware units. They have been included as units for convenience in computation. Unit 903 is the probability of not acquiring the wrong target during earth acquisition. There is a command (roll override), represented by reliability unit 307, that is redundant to this probability. This same relation of these units occurs again after midcourse maneuver. For simplification in the equations, this is shown during the midcourse maneuver in the tabulation.

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EXHIBIT 16 - STATE OF UNITS IN NORMAL ROUTE

	Injection t_0 – Begin Sun Acquisition t_1	Begin Sun Acquisition t_1 – Complete Sun Acquisition t_2	t_2 – Begin Earth Acquisition t_3	Begin Earth Acquisition t_3 – Complete Earth Acquisition t_4	t_4 – Begin M/C Maneuver t_5	Begin M/C Maneuver t_5 – End M/C Maneuver $t_6 = 190$	t_6 – Begin Encounter $t_7 = 2590$	Begin Encounter t_7 – End t_8	Remarks
Unit	.5 hr	.5 hr	166 hrs	.5 hr	19.5 hrs	3 hrs	2400 hrs	.5 hr	
101	(1)						u(2)	u	
102								u	
103								u	
104							u	u	
105							u	u	
106							u	u	
107							u	u	
108							u	u	
109							u	u	
201	e(3)	u	u	u	u	u	u		
202	e	u	u	u	u	u	u		
203	e	u	u	u	u	u	u		
204	e	u	u	u	u	u	u		
205	e	u	u	u	u	u	u		
206	e	u	u	u	u	u	u		
207	e	u	u	u	u	u	u		
208	e	u	u	u	u	u	u		
241	e	u	u	u	u	u	u		
242	e	u	u	u	u	u	u		
243	e	u	u	u	u	u	u		
244	e	u	u	u	u	u	u		
245	e	u	u	u	u	u	u		
246	e	u	u	u	u	u	u		
247	e	u	u	u	u	u	u		

EXHIBIT 16 (Continued)

	Injection	Begin Sun Acquisition	Complete Sun Acquisition	Begin Earth Acquisition	Complete Earth Acquisition	Begin M/C Maneuver	End M/C Maneuver	Begin Encounter	End
	t_0	t_1	t_2	t_3	t_4	t_5	$t_6 = 190$	$t_7 = 2590$	t_8 Remarks
Unit	.5 hr	.5 hr	166 hrs	.5 hr	19.5 hrs	3 hrs	2400 hrs	.5 hr	
248	e	u	u	u	u	u	u		
249	e	u	u	u	u	u	u		
250	e	u	u	u	u	u	u		
251	e	u	u	u	u	u	u	u	
252	e	u	u	u	u	u	u		
280	e	u	u	u	u	u	u		
281	e	e	e	e	e	e	u	u	
282	e	u	u	u	u	u	u	u	
283	e	u	u	u	u	u	u	u	
284	e	u	u	u	u	u	u	u	
285	e	u	u	u	u	u	u	u	
286	e	u	u	u	u	u	u	u	
287	e	u	u	u	u	u	u	u	
288	e	u	u	u	u	u	u	u	
301	e	u	u	u	u	u	u	u	
302	e	u	u	u	u	u	u	u	
303	e	u	u	u	u	u	u	u	
304	e	u	u	u	u	u	u	u	
305	e	e	e	e	u				
306						u(4)			
307				0(4)(5)		0(4)			Associated unit = 903
308							0	0	Associated units = 407, 902
309							0	0	Associated units = 407, 902
310									Omitted from analysis
311									Omitted from analysis

EXHIBIT 16 (Continued)

	Injection t_0 – Begin Sun Acquisition t_1	t_1 – Complete Sun Acquisition t_2	t_2 – Begin Earth Acquisition t_3	t_3 – Complete Earth Acquisition t_4	t_4 – Begin M/C Maneuver t_5	t_5 – End M/C Maneuver t_6 = 190	t_6 – Begin Encounter t_7 = 2590	t_7 – End t_8	Remarks
Unit	.5 hr	.5 hr	166 hrs	.5 hr	19.5 hrs	3 hrs	2400 hrs	.5 hr	
312								$0^{(4)}$	Associated units = 410, 406
313									Omitted from analysis
314	0								Associated units = 405, 408
315									Omitted from analysis
316									Omitted from analysis
317				$0^{(4)}$		$0^{(4)}$			Associated unit = 404
401	u	u	u	u	u	u	u	u	
402	u	u	u	u	u	u	u	u	
403	u	u	u	u	u	u	u	u	
404	e	e	e	0	e	0			Associated unit = 317
405	0								Associated unit = 314
406	u	u	u	u	u	u	u	0	Associated unit = 312
407	e	e	e	e	e	e	0		Associated units = 902, 308, 309
408	0								Associated unit = 314
410	e	e	e	e	e	e	e	$0^{(4)}$	Associated unit = 312
411									Omitted from analysis
412	e	e	e	e	u	u			
413	e	e	e	e	u	u			
414	e	e	e	e	u	u			
415	e	e	e	e	u	u			
501	e	u	u	u	u	u	u	u	
502	e	u	u	u	u	u	u	u	
503	e	u	u	u	u	u	u	u	
504	e	u	u	u	u	u	u	u	

EXHIBIT 16 (Continued)

	Injection t_0 – Begin Sun Acquisition t_1	Begin Sun Acquisition t_1 – Complete Sun Acquisition t_2	Complete Sun Acquisition t_2 – Begin Earth Acquisition t_3	Begin Earth Acquisition t_3 – Complete Earth Acquisition t_4	Complete Earth Acquisition t_4 – Begin M/C Maneuver t_5	Begin M/C Maneuver t_5 – End M/C Maneuver $t_6 = 190$	End M/C Maneuver t_6 – Begin Encounter $t_7 = 2590$	Begin Encounter t_7 – End t_8	Remarks
Unit	.5 hr	.5 hr	166 hrs	.5 hr	19.5 hrs	3 hrs	2400 hrs	.5 hr	
505	e	u	u	u	u	u	0	0	Associated unit = 902
601	e	u	u	u	u	u	u	u	
602	e	u(4)		u(4)		u(4)	0(4)	0(4)	Associated unit = 902
603	e	u	u	u	u	u	u	u	
604	e	u	u	u	u	u	u	u	
605	e	e	e	u	u	u	u	u	
606	e	e	e	u	u	u	u	u	
607	e	u(4)		u(4)		u(4)	0	0(4)	Associated unit = 902
608	e	e	e	u	u	u	u	u	
701						u			
702						u(4)			
703						u(4)			
801				u	u	u	u	u	
802	e	u	u	u	u	u	u	u	
803	e	u	u	u	u	u	u	u	
804	e	u	u	u	u	u	u	u	
805	e	e	e	e	e	e	e	e	
806	e	e	e	e	e	e	e	e	
807	e	u	u	u	u	u	u	u	
808	e	u	u	u	u	u			
809				u	u	u	u	u	
810	e	u	u	u	u	u			
901	e	u	u	u	u	u	u	u	
902							u(6)	u(6)	
903				u(6)		u(6)			

Notes:

(1) A space left blank indicates that the unit is not needed during this particular interval.

(2) u = required.

(3) e = energized.

(4) Non-time-dependent.

(5) 0 = required in a redundant capacity.

(6) These are not "units" in the usual sense, but are probabilities that an event will not occur in the time interval indicated (902--probability of no noncatastrophic impact; 903--probability of not acquiring the wrong target).

The other nonhardware unit is similar. Unit 902 is the probability of no noncatastrophic impact during cruise. Allowance has been made in the Mariner mission for at least two such impacts. The reliability units that are associated with the back-up command to correct the attitude control after such impacts are 307, 308, and 407. These are listed in a redundant capacity.

After the midcourse maneuver, the spacecraft enters its 2400-hour cruise phase. Now the cruise science data units are required to be operational as well as all engineering data units. The power supply units, transponder, and attitude control units, except for the gyros, are needed in a primary or "in-line" capacity. The gyros, units 602 and 607, are needed in a redundant capacity only in association with unit 902 (the probability of no noncatastrophic impact).

The last of the mission sequence, encounter, requires about 30 minutes. Units 102 and 103 (planet science units) are required, as well as other cruise science units. Because of the short time (half-hour), the encounter is assumed in the computation to be completed at 2590 hours.

The state of each reliability unit in the normal route is given in detail by major event of the total mission in Exhibit 16.

C. Mathematical Reliability Models

For a mission as complex as that of the Mariner R, with many possible degraded states of operation, it is recognized that the classical measure of reliability, based primarily on the probability of survival, is unsuitable. During a spacecraft mission, for example, degraded performance might be manifested as the ability to perform only certain of the experiments. It is evident, however, that having the capability to perform these experiments certainly contributes to mission success. Accordingly, any measure of spacecraft reliability must consider the broad spectrum of spacecraft operations, ranging from perfect operation down to the lowest level of degraded, but acceptable, operation.

The figure-of-merit (FOM) model attempts to reflect the effects of these degraded modes in a realistic manner. To provide the necessary background for comparisons of the classical reliability model and the

FOM model, the classical model is first briefly described below. This is followed by a general description of the FOM model.

1. The Classical Model

Consider a spacecraft as consisting of n functional units. These spacecraft units provide "services" to another group of m black boxes which perform the experiments: the services including, for example, supplying power, transmitting experimental information, and maintaining a prescribed space orientation.

Next, define spacecraft "hardware states," S_i, in terms of the condition of operability (i.e., failed or not failed) of the n spacecraft units. It is clear that the collection of such states ranges from the "perfect" state, wherein all units are operable, through states defined by varying combinations of operable and inoperable units, down to the "dead" state, in which every unit is inoperable. The total number of possible spacecraft states is 2^n.

The next step of the classical reliability approach is to split the totality of such states into acceptable and nonacceptable states. This is often done by ordering all such states according to their desirability, starting with the perfect state and going down to the dead state. Then somewhere in this ordering, a line is drawn, above which all states are defined to be acceptable and below which all states are nonacceptable.

Finally, the classical definition of mission reliability, $R(t)$, is simply the probability that, at any time t, the system is in an acceptable state. Mathematically, $R(t)$ is expressed as

$$R(t) = \sum P(S_i, t) \tag{1}$$

where $P(S_i, t)$ is the probability that the spacecraft is in state S_i at time t; and the summation is taken over all acceptable states. The probability appearing in Equation (1) can be expressed in terms of the reliability of the black boxes that define the corresponding states.

More explicity, each S_i is defined by the set, O_i, of operable spacecraft units and the set, I_i, of inoperable spacecraft units. Assuming independence of these units, $P(S_i)$ is given by the expression,

$$P(S_i) = \left[\prod_{j \in O_i} R_j(t)\right]\left[\prod_{j \in I_i}\left\{1 - R_j(t)\right\}\right] \tag{2}$$

where $R_j(t)$ is the reliability of the j^{th} spacecraft unit or redundant group of units $(1 \leq j \leq n)$ at time t. It is assumed that the components in the spacecraft fail according to the exponential law; i.e., the probability of a component failing in any given incremental time period is equal to the probability that it fails during any other time period of the same duration (constant failure rate). Thus, the probability that the j^{th} unit has not failed up to time t is

$$P_j(t) = e^{-\lambda_j t} \tag{3}$$

where λ_j is the failure rate of the unit. If the unit is in series, the previously discussed $R_j(t)$ is equal to $P_j(t)$. If several units are in a redundant configuration, $R_j(t)$ is determined by the appropriate combination of $P_j(t)$'s.

A very practical question which can be answered by the classical model concerns the reliability of a function, subsystem, or a mission event without regard to the operability of those units not directly concerned with that function subsystem, or event. This is equivalent to requiring the computation that a specific group of the states S_i be added or lumped together to give the total probability that some set of units O_i be operable while the remaining units I_i are either up or down. Such a computation is readily accomplished by dropping the second factor from the expression (2) giving

$$R_f(t) = \prod_{j \in O_i} R_j(t) \tag{4}$$

where $R_f(t)$ is the reliability of a function or event, O_i is the set of all units required for the function or event, and the other symbols have the previously assigned meanings. It is this particular expression of the classical model which has been exercised to ascertain the reliability of the Mariner spacecraft.

It has been noted that where $R_j(t)$ represents the reliability of a redundant group rather than a single, in-line unit, its numerical evaluation depends upon the particular reliability configuration within the group. In many instances, it is possible to reduce the group to a set W of equivalent units in parallel configuration. This can in turn be reduced to a single reliability by the expression

$$R_j(t) = 1 - \prod_{k \in W} \left[1 - R_k(t)\right] \tag{5}$$

where $R_j(t)$ is the reliability of the j^{th} group of W redundant units, each with reliability $R_k(t)$.

2. Figure-of-Merit Model

In the FOM model, mission values are assigned to the various objectives of the mission such as midcourse maneuver, cruise science data, planet science data, etc. Mission objectives are divided into two categories; (1) "one-shot" events such as midcourse maneuver which accrue value at a specified time and (2) continuing events such as transmitting cruise science data which accrue value over a period of time. For the former, we denote the mission value accrued by event α as V_α . The value accrual rate (value accrued per hour) for a continuing event, β , is generally a function of time. For instance, engineering data is more valuable before execution of the midcourse maneuver than after. The value accrual rate at time t for objective β is denoted by $v_\beta(t)$. The total value of a mission in which there are no equipment failures is assumed to be 100 percent. Thus, the maximum mission value V_M is

$$V_M = 100 = \sum_\alpha V_\alpha + \sum_\beta \int v_\beta(t)\, dt \tag{6}$$

where α is summed over all one-shot objectives, β summed over all continuous objectives, and t is integrated over the times during which these values are to be accrued.

Next we determine the probabilities of successfully performing the one-shot events. Assume that in order to perform event α , certain units are required to be operable for time t. Let $R_j(t)$ denote the reliability of the j^{th} unit if it is in series reliability-wise or group of units in the case of a redundant configuration. The probability of performing event α is

$$P_\alpha = \prod_j R_j(t) \tag{7}$$

For the continuous events we determine the probability that the required units are operable at time t. Denoting the probability of being able to obtain value from objective β at time t by $P_\beta(t)$ we have

$$P_\beta(t) = \prod_j R_j(t) \tag{8}$$

where j is taken over all units required for function β and $R_j(t)$ is the probability that the j^{th} unit or redundant group of units is operable at time t.

The average (or expected) value of a mission objective is simply the product of the value assigned to that objective and the probability that the objective is successfully met. Thus, the average value $\bar{V}_\alpha$ for a (one-shot) objective α is

$$\bar{V}_\alpha = V_\alpha P_\alpha \tag{9}$$

For objectives which accrue value continuously, the average rate $\bar{v}_\beta(t)$ of value accrual at time t is (for objective β)

$$\bar{v}_\beta(t) = v_\beta(t)\, P_\beta(t) \tag{10}$$

The total average value $\bar{V}_\beta$ accrued during the mission for objective β is

$$\bar{V}_\beta = \int v_\beta(t)\, P_\beta(t)\, dt \tag{11}$$

where the integration is taken over the complete mission with $V_\beta(t) = 0$ for all t where β is not needed.

The average value for a complete mission, $\bar{V}_M$, is determined by combining the average values for each of the objectives. Thus, we have

$$\bar{V}_M = \sum_\alpha V_\alpha P_\alpha + \sum_\beta \int v_\beta(t) P_\beta(t) dt \tag{12}$$

which is the figure-of-merit. It should be noted that $\bar{V}_M$ is an expected value in a statistical sense.

D. Value Apportionment

Complete mission success through planet encounter is assumed to yield a value of 100 percent. The contribution to this total mission value by the successful completion of various objectives during the mission were assigned as shown in Exhibit 17. The values for the seven primary objectives were arrived at by the Systems Design Section of Jet Propulsion Laboratories by obtaining value assignments from a number of cognizant personnel and averaging these estimates. Based on these averages, assignments were made for the subobjectives. The value accrual rates were determined for those objectives which are continuous with time. Entries 1, 2, 6, and 7 are essentially "one-shot" events since they are executed in a relatively short period of time. Thus, their values are assumed to accrue at the time indicated. Entries 3, 4, and 5 are assumed to accrue value continuously throughout the time period specified.

The successful completion of midcourse maneuver is assumed to contribute a value of 15.1 percent 190 hours after injection. The subsequent sun and earth acquisitions and change from omni to directional antenna are also assumed to introduce their value contributions at 190 hours. The sun and earth acquisitions which are to be performed before midcourse maneuver are not assigned value since if either is unsuccessful, midcourse maneuver cannot be executed. The acquisitions after midcourse maneuver contribute a total of 5.8 to the mission value.

EXHIBIT 17 - VALUE APPORTIONMENT FOR MISSION OBJECTIVES

	Value	Subtotals	Time (hours)
1. Midcourse Maneuver	15.1		190
2. Acquisition	5.8		190
a. Sun		2.3	
b. Earth		2.3	
c. Change to directional antenna		1.2	
3. Tracking	11.6		0-2590
a. Two-way		11.6	
b. One-way		3.5	
4. Engineering Data	14.0		0-2590
a. Decks A and B		5.8	
b. Deck C		1.2	
c. Deck D		2.9	
d. Decks E and F		2.3	
e. Event registers		1.2	
f. Command monitor		.6	
5. Cruise Science Data	15.1		190-2590
a. Ions, particles, dust		7.0	
b. Plasma, magnetometer		8.1	
6. Reach Planet Neighborhood With Tracking	9.3		2590
7. Planet Science Data	29.1		2590

The event of reaching the planet neighborhood with tracking capability (either two - or one-way tracking) is assumed to add a value step of 9.3 percent at encounter (2590 hours after injection). Although the encounter phase is to last for 67 hours, the experiments are in view of the planet for less than a half hour. Therefore, it is assumed that the planet science data value is all accrued in step fashion at the time of encounter, 2590 hours.

The values of tracking and engineering data are assumed to accrue throughout the mission from injection to encounter while cruise science data accrue from the time of completion of the midcourse maneuver until encounter. Exhibit 18 shows the rates of value accrual for tracking, engineering data, and cruise science data as assigned by Jet Propulsion Laboratory. In actuality, the rates would probably be continuous functions of time; e.g., tracking would contribute a diminishing amount of value per unit time near the end of the mission relative to the beginning. In order to make the problem tractable, however, the mission was divided into four periods and the accrual rates for data and tracking were assumed to be constant within each period. The first period, from 0 to 190 hours, represents time until completion of the midcourse maneuver; the end of the second period, 550 hours, was chosen to reflect the effect of diminishing value of tracking and engineering data as the mission progresses. The end of the third period, 2350 hours, was chosen to reflect the increase in value of the cruise science data as the vehicle nears the planet. The end of the fourth period is the time of encounter.

The normal operation of the tracking equipment results in two-way tracking. One-way tracking, which can be performed when the standby crystal oscillator is functioning, also contributes value to the mission but at a much lower rate. The two tracking modes are mutually exclusive so the value indicated for tracking throughout the mission (11.6) represents that accrued with two-way tracking only.

Engineering data has been divided into the six categories listed for purposes of the figure-of-merit computations. The channel assignments for the various engineering telemetry decks are listed in Exhibit 19. Cruise science data includes two categories; the first being digital data

EXHIBIT 18 - VALUE ACCRUAL RATES (x 10^{-3})

	Time (hours)			
	0-190	190-550	550-2350	2350-2590
Tracking (11.6)				
Two-way	30.59	6.47	1.71	1.71
One-way	9.18	4.85	0	0
Engineering Data (14.0)				
Decks A and B	12.250	3.233	1.140	1.140
Deck C	.449	.449	.449	.449
Deck D	6.117	.727	.727	.727
Decks E and F	.898	.898	.898	.898
Event registers	4.594 (1)	.121	.121	.121
Command monitor	.112	.112	.112	.112
	24.420	5.540	3.447	3.447
Cruise Science Data (15.1)				
Ions, particles, etc.	0	2.154	2.154	9.69
Plasma, magnetometer	0	2.154	2.154	14.54
	0	4.308	4.308	24.23
Total (40.7)	55.01	16.318	9.465	29.387

Note: (1) A value of .29 is added at completion of midcourse maneuver.

EXHIBIT 19 - DATA CHANNEL ASSIGNMENTS

A and B Decks

High-Rate words With Isolated Power Supplies:

A3 Yaw control gyro
A4 Pitch control gyro
A5 Roll control gyro
A7 Pitch sun sensor
A8 Yaw sun sensor
A9 Roll error
B2 Earth brightness
B5 L-band AGC
B6 L-band phase error (coarse)

High-Rate Words:

A0 Sync word
A2 Battery voltage
A6 Battery current drain
B3 Antenna reference hinge angle
B4 Antenna hinge position
B7 Propellant tank pressure
B8 Battery charger current
B9 Motor nitrogen pressure

C Deck Words

C0 Sync word
C4 L-band phase error (fine)
C5 L-band directional power
C6 Louver position

D Deck Words

D0	Sync word
D1	Low reference
D2	Panel 4A11 voltage
D3	Omni antenna power
D4	A/C nitrogen pressure
D5	Panel 4A11 current
D7	Panel 4A12 voltage
D8	Panel 4A12 current
D9	High reference

E Deck Words

E0	Reference temperature
E1	Booster regulator temperature
E2	Motor nitrogen tank temperature
E3	Propellant tank temperature
E4	Earth sensor temperature
E5	Battery temperature
E6	A/C nitrogen temperature
E7	Panel 4A11 front temperature
E8	Panel 4A12 front temperature
E9	Panel 4A11 back temperature

F Deck Words

F0, F1, F2, F3, F4	Electronic assembly temperature
F5	Lower thermal shield temperature
F6	Upper thermal shield temperature
F7	Plasma Electrometer temperature
F8	Antenna yoke temperature

and the second analog data. Again, this decision was necessitated by the figure-of-merit model. The rationale for the various divisions of engineering and science data will be discussed further in the next subsection.

E. Numerical Evaluation

1. Classical Reliability Calculations

Application of the classical model to the units selected for the Mariner spacecraft permits the evaluation of numerical reliabilities for a variety of interesting equipment groups or significant events. The equations used to calculate these reliabilities all tend to follow the forms shown in the classical model, but in many cases they contain large numbers of multiplicative terms. Repetitive multiplications can be avoided in the computations by summing failure rates of in-line units, which is a simplification made possible by the assumption of the exponential failure law. Accordingly, the functions or events discussed here are described by detailing the units which comprise the set, O_i, of operable units and it is understood that all remaining units do not enter into the computations.

a. Power Supply

The reliability of the power supply involves the operability of the following units: 501, 502, 503, 504, and 505. All units are in series for complete operability of the supply; however, the failure rate of unit 501 is modified slightly by the necessity of erecting the solar array. This latter event has a probability of .999397 of successfully occurring, and the computation for this is detailed in Appendix A. The sum of the failure rates for these units is 126×10^{-6} (failures per hour). If this sum is denoted as λ_{ps} and the probability of successful deployment as P(dp) the reliability of this subsystem at any time, t, is given by

$$R_{ps}(t) = P(dp)\, e^{-\lambda_{ps} t} \tag{13}$$

This has been evaluated at three values of t as listed.

Midcourse maneuver:	$t = 190$	$R_{ps}(190) = .9758$
Cruise breakpoint:	$t = 550$	$R_{ps}(550) = .9326$
Encounter:	$t = 2590$	$R_{ps}(2590) = .7159$

b. <u>Transponder</u>

In the coherent or two-way mode, transponder operability through the midcourse maneuver requires units 802, 803, 804, 807, 808, and 810. This implies transmission via the omni antenna and the sum of the failure rates is 141×10^{-6}. Beyond 190 hours, transmission is normally via the directional antenna. Ignoring the potential redundancy of the omni antenna, it is necessary that units 802, 803, 804, 807, 801, and 809 be operable beyond 190 hours. Because of the symmetry of equipment, this set of failure rates also sums to $141 \times 10^{-6} = \lambda_{coh}$. Accordingly, operation for any time, t, is characterized by a reliability

$$R_{coh}(t) = e^{-\lambda_{coh} t} \quad . \tag{14}$$

This has been evaluated at three values of t, as listed.

Midcourse maneuver:	$t = 190$	$R_{coh}(190) = .9736$
Cruise breakpoint:	$t = 550$	$R_{coh}(550) = .9254$
Encounter:	$t = 2590$	$R_{coh}(2590) = .6876$

In the noncoherent or one-way mode, the operable units include 802, 804, 805, 806, 807, 801, and 809 for $t > 190$. Operation in the noncoherent mode for the period prior to midcourse maneuver is not considered here. The sum of the failure rates is $\lambda_{nch} = 53.6 \times 10^{-6}$. Reliability to any time, t, beyond 190 hours is given by

$$R_{nch}(t>190) = R_{coh}(190)\left[e^{-\lambda_{nch}(t-190)}\right] \tag{15}$$

Upon evaluation, this yields:

Cruise breakpoint: $t = 550$ $R_{nch}(550) = .9550$

Encounter: $t = 2590$ $R_{nch}(2590) = .8530$

c. Attitude Control

Because of the short operating time, the acquisition of sun and earth are accomplished with high reliability. Of interest here is the reliability of maintaining stability once acquired. For sun tracking, units 601, 603, and 604 are necessary. The failure rate of this group is $\lambda_{st} = 38.6 \times 10^{-6}$. The reliability for two operating periods is

Cruise breakpoint: $t = 550$ $R_{st}(550) = .9790$

Encounter: $t = 2590$ $R_{st}(2590) = .9026$

If the added task of earth tracking is superimposed on the sun tracking function, the complement of operable units becomes 601, 603, 604, 605, 606, and 608, and these have a total failure rate $\lambda_{set} = 432 \times 10^{-6}$ Evaluating the reliability at two operating points gives

Cruise breakpoint: $t = 550$ $R_{set}(550) = .7884$

Encounter: $t = 2590$ $R_{set}(2590) = .3172$

d. Command Capability

A relatively large number of units in series is required for the successful reception and decoding of commands. This includes several units of the transponder and data encoder as well as the command detector and decoder. The units which are needed at all times include 248, 249, 250, 251, 252, 280, 282, 283, 284, 286, 287, 288, 803, 804, 802, 807, 301, 302, 303, 304, 308, 309, and 312. Certain commands are not needed after particular events; in addition to the above unit, unit 314 is needed for 5 hours, unit 317 is needed for 167 hours, and units 305, 306, and 307 are needed for 190 hours. Units 801 and 809 are redundant to units 808 and 810 for the period from 190 hours to 1008 hours (the limit of the omni antenna), but this is not considered significant in this approximate calculation. The specification of a requirement for transmission of the detector monitor signal, which adds a large number of units to the set, is predicated on the assumption that commands are not desirable without this telemetered information. Failure rates for the units required at all times sum to 547×10^{-6}. For the single commands, units 314 and 317, the failure rates are 4.58×10^{-6} For the stored commands, units 305 and 306, the failure rate is 25.3×10^{-6}. Reliability is viewed as the availability of all commands required up to any time, t.

Midcourse maneuver:	$t = 190$	$R_{com}(190) = .8964$
Cruise breakpoint:	$t = 550$	$R_{com}(550) = .7362$
Encounter:	$t = 2590$	$R_{com}(2590) = .2327$

e. Central Computer and Sequencer

Given that other subsystems aboard the spacecraft are operating as required, it is of interest to inquire about the reliability of obtaining certain signals from the CC and S. The first signal of importance is derived from the launch matrix and initiates the deployment of the solar array and turns on the attitude control power. For this signal, the series units are 401, 402, 403, 405, and 408. The sum of the failure rates is 107×10^{-6} and the operating time is 5 hours. At 167 hours a signal to remove the inhibit from earth acquisition is given. To obtain this and the previous signal requires operability of units 405 and 408 for 5 hours, and 401, 402, 403, and 404 for 167 hours. Failure rates of units 405 and 408 sum to 13.7×10^{-6} and for the group 401, 402, 403, and 404 they sum to 106×10^{-6}.

The portion of the CC and S which processes the stored commands is required for the midcourse maneuver, through 190 hours after launch. This involves units 401, 402, 412, 413, 414, and 415 which have a combined failure rate of 292×10^{-6}. Previous signals demand operability of units 403 and 404 with a total failure rate of 25.7×10^{-6} for 167 hours, and units 405 and 408 for 5 hours as before. Finally, the CC and S must provide the encounter start signal at 2590 hours. This is accomplished by units 401, 402, 403, 406, 407, and 410 with a combined failure rate of 117×10^{-6}. To assure the generation of previously required midcourse signals, units 412, 413, 414, and 415 with a total failure rate of

211×10^{-6} must remain operable for 190 hours. In addition, unit 404 must be intact for 167 hours and units 405 and 408 must function for 5 hours.

Computation of these probabilities is straightforward and results in the following reliabilities:

Solar array deployment and A/C power on signal	.9995
Initial earth acquisition signal together with previous signals	.9823
Midcourse maneuver signals together with previous signals	.9427
Encounter start signal together with previous signals and the update pulse	.7078

f. Science Measurements

Considering cruise science only, the equipment required to be operable for the mission is the group of units 101, 104, 105, 106, 107, 108, and 109. Their failure rates sum to 269×10^{-6} and they are energized for the entire mission. Cruise science reliability, $R_{cs}(t)$, is, therefore,

Cruise breakpoint:	$t = 550$ hours	$R_{cs}(550) = .8628$
Encounter:	$t = 2590$ hours	$R_{cs}(2590) = .4993$

If the reliability of planet science equipment is included, and if it is assumed that this added equipment is energized throughout the mission, the total failure rate rises to 302×10^{-6} and $R_{cs}(2590)$ is lowered to .4561.

g. Medium and Low-Deck Data Encoding

This portion of the data encoder comprises units 201A through C, 202A through F, 203A through J, 204A through I, 205A through I, 206, 207, 208, and 242A. The failure rate covering this group is 253×10^{-6}. This equipment only is considered here and none of the remaining data encoder units or transponder units enter into the calculations. The reliability, $R_{ld}(t)$, is computed for three time periods.

Midcourse maneuver:	$t = 190$	$R_{1d}(190) = .9531$
Cruise breakpoint:	$t = 550$	$R_{1d}(550) = .8703$
Encounter:	$t = 2590$	$R_{1d}(2590) = .5112$

h. Complete Data Encoder

If all of the data encoder is assessed, the units listed under (g) above are required, and, additionally, units 241A through I, 242B through R, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 280, 281, 282, 283, 284, 285, 286, 287, and 288. This latter group of units has a combined failure rate of 456×10^{-6} which, when added to the medium and low-deck units, gives a total failure rate for the data encoder of 709×10^{-6}. With this rate, the data encoder reliability, $R_{de}(t)$, for three time periods is

Midcourse maneuver:	$t = 190$	$R_{de}(190) = .8741$
Cruise breakpoint:	$t = 550$	$R_{de}(550) = .6773$
Encounter:	$t = 2590$	$R_{de}(2590) = .1522$

i. Normal Mission

The calculation of classical reliability for the entire spacecraft in the normal mission is derived from Exhibit 16 in subsection IV.B. There are alternative ways of performing such a computation and the results will vary to some extent. For this study it was decided to select points in time and to compute the reliability of only the equipment which was needed up to each point in time. Thus, for example, the reliability of the normal mission through 167 hours does not include the effects of possible failures in the midcourse maneuver, but the calculation for the 190-hour period does include such failure probabilities. All redundancies indicated by the unit selection diagrams have been included, and units which serve no function after any given time are excluded from the calculations beginning at that time. The spacecraft reliability has been computed for seven points in time on this basis and these are tabulated in Exhibit 20.

Exhibit 21 shows these points plotted as a function of time. It is reiterated that these classical reliability predictions are based on the

EXHIBIT 20 - SPACECRAFT CLASSICAL RELIABILITY FOR THE NORMAL MISSION

Time	Reliability
1 hour	.9972
167 hours	.8081
167.5 hours	.7506
187 hours	.7210
190 hours	.6931
1200 hours	.1130
2590 hours	.0104

62-462

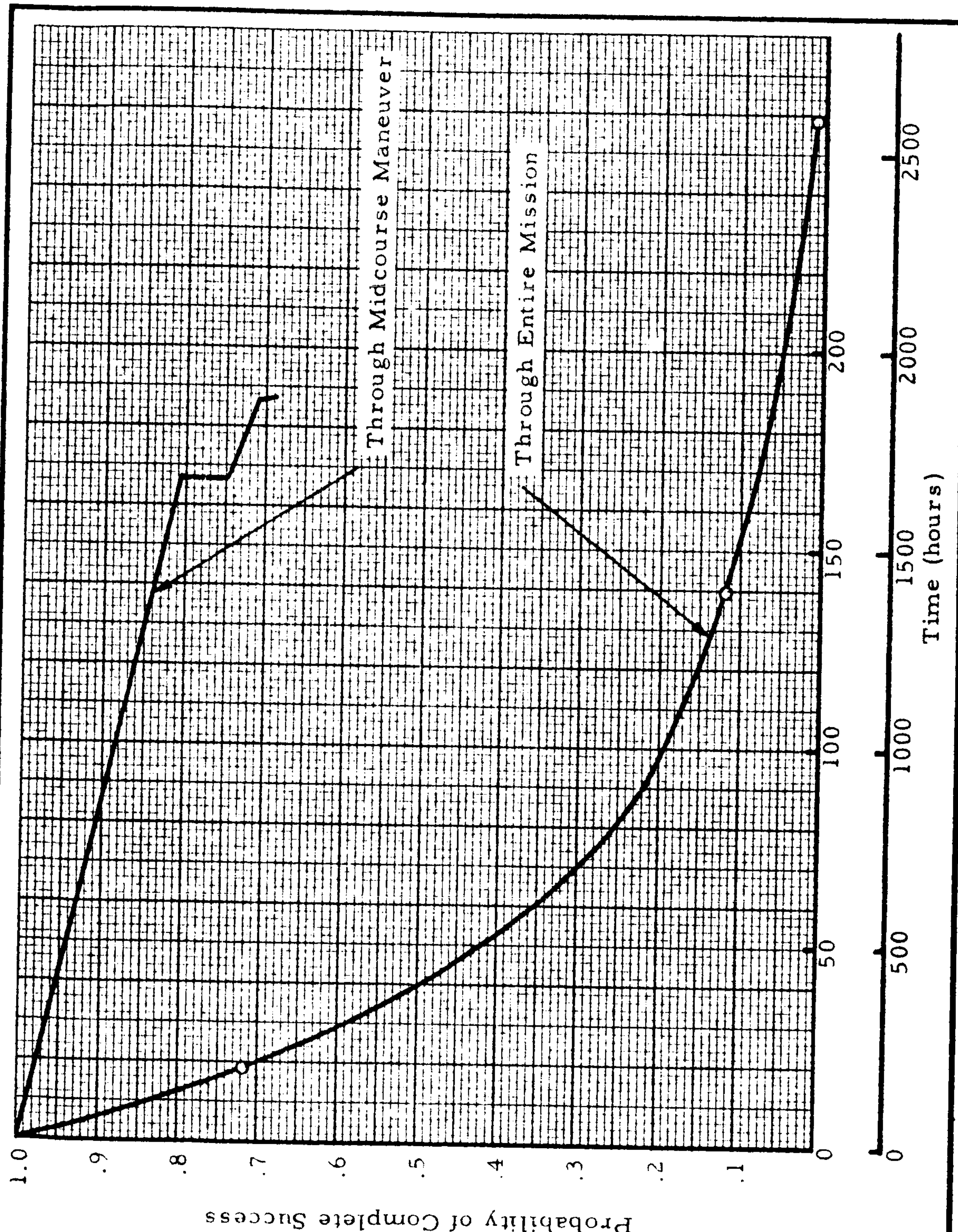

EXHIBIT 21 - PROBABILITY OF COMPLETE MISSION SUCCESS

assumptions which underlie this study and do not reflect the possible use of special low-failure-rate parts or subtle circuit design techniques which might be employed to extend the useful operating life of active elements. To this extent they have limited usefulness when treated as absolute measures of reliability. Relative to each other and to contemplated design changes, they assume considerable significance and offer an important design tool.

2. Figure-of-Merit

a. Midcourse Maneuver and Acquisition

The computations for the average values were performed separately for each of the seven mission objectives listed in Exhibit 17 and then combined using Equation (12) to obtain the total mission average value. Initially, the computations for the midcourse maneuver are discussed. The average or expected value of the midcourse maneuver is equal to the product of the value assigned to this objective (denoted the maximum value) and the probability that it is successfully completed. Exhibit 22 lists the units which must operate for successful midcourse maneuver, the failure rate of each unit (from Exhibit 15), the time during which each unit might operate, and the redundancy involved. The redundancy is functional only and involves the Command Detection and Decoding equipment and the Central Computer and Sequencer. The time durations for unit operations are taken from Exhibit 16. For units which are required only during earth acquisition, (e.g., unit 607) the time period is assumed to be a half hour. The same is true of sun acquisition, while the units required only during midcourse maneuver (other than one-shot devices) are assumed to operate for three hours.

The probability that unit j operates successfully for the required t_j hours is equal to

$$P_j(t_j) = e^{-\lambda_j t_j} \tag{16}$$

EXHIBIT 22 - UNITS REQUIRED FOR MIDCOURSE MANEUVER

Unit	Failure Rate, $\lambda \times 10^{-6}$	Time Required (Hours From Injection)	Comments
301	4.82	0-190	Series
302	71.32	0-190	Series
303	30.55	0-190	Series
304	18.24	0-190	Series
305	16.11	0-187	Series
306	4.58	187-190	1 time only
307	4.58	167-167.5, 187-190	Redundant to 903, 1 time in each interval
314	4.58	0-.5	Redundant to 405, 408
317	4.58	167-167.5, 187-190	Redundant to 404
401	6.45	0-190	Series
402	74.28	0-190	Series
403	13.02	0-190	Series
404	12.64	0-167, 167.5-187	Series
		167-167.5, 187-190	Redundant to 317
405	10.15	0-.5	Series with 408, redundant to 314
406	16.30	0-190	Series
408	3.57	0-.5	Series with 405, redundant to 314
412	61.31	0-190	Series
413	84.86	0-190	Series
414	29.98	0-190	Series
415	35.01	0-190	Series
501	37.70	0-190	Series, without pyrotechnics
	Prob. = .999397	0-.5	Probability of deployment of solar panels
502	31.16	0-190	Series
503	11.06	0-190	Series
504	20.67	0-190	Series

EXHIBIT 22 (Continued)

Unit	Failure Rate, $\lambda \times 10^{-6}$	Time Required (Hours From Injection)	Comments
505	24.99	0-190	Series
601	3.49	0-190	Series
602	611.86	0-1, 167-167.5, 187-190	1 time each interval
603	11.80	0-190	Series
604	23.28	0-190	Series
605	299.38	0-190	Series
606	85.88	0-190	Series
607	302.23	0-1, 167-167.5, 187-190	1 time each interval
608	8.33	0-190	Series
701	57.93	187-190	Series
702	113.89	187-190	1 time only
703	690.4	187-190	1 time only
802	10.7	0-190	Series
803	91.12	0-190	Series
901	17.0	0-190	Series
903	Prob. = .93	167-167.5, 187-190	Redundant to 307, 1 time in each interval

The probability of successful operation of every unit required through midcourse maneuver is

$$P_{MC} = P_S \times P_R \qquad (17)$$

where P_S is the reliability of all units in series and P_R is the reliability of the units which are functionally redundant. The former is equal to

$$P_S = \prod_j P_j(t_j) \qquad (18)$$

where j is taken over all units in series and t_j is the time the j^{th} unit is required to operate (refer to Exhibit 22).

Unit 903 listed in Exhibit 22 refers not to a hardware unit, but rather to the event of not acquiring the moon. The probability associated with this is accrued to be .97. If the moon is acquired, unit 307, command gate and switch for roll override, may be used to cause reacquisition. Thus, the probability that acquisition does not fail because of falsely acquiring the moon is equal to the probability that not both "units" 903 and 307 "fail"; that is, that either the moon is not acquired or if it is, that the roll override operates correctly. Other redundancies involved in the midcourse maneuver are the command for A/C power and solar array deployment and the command for earth acquisition. The former may be performed by either unit 314 in the Command Detection and Recording equipment, or units 405 and 408 in the CC and S. The latter may be performed by either unit 317 or unit 404. Thus, the redundant portion of the expression for the probability of successful midcourse maneuver is

$$\begin{aligned} P_R = & \left\{1 - \left[1 - P_{903}(3.5)\right]\left[1 - P_{307}(3.5)\right]\right\} \\ & \times\left\{1 - \left[1 - P_{405}(.5)P_{408}(.5)\right]\left[1 - P_{314}(.5)\right]\right\} \\ & \times\left\{1 - \left[1 - P_{404}(3.5)\right]\left[1 - P_{317}(3.5)\right]\right\} \end{aligned} \qquad (19)$$

where the subscripts refer to the unit designations and the times are in hours. The probability of successful midcourse maneuver computed from these equations is

$$P_{MC} = 0.800$$

Also of interest is the probability that the midcourse maneuver fails to be executed, but all other required functions can be performed such as generating power, sun and earth acquisition and tracking, etc. In this case much valuable engineering and science data can be obtained from the spacecraft in the cruise phase; only that value obtained from encountering the planet is lost. This event can occur if any one of the following units fail: 701, 702, 703, 305, 306, 412, 413, 414, or 415. The probability of any of these units failing and the rest of the units listed in Exhibit 22 being operable through 190 hours is

$$P_{NMC} = .036$$

After midcourse maneuver is completed, earth and sun reacquisition must be performed. Given that midcourse maneuver was successful, the only units which must operate that were not required at completion of the maneuver are 607, roll gyro and electronics for earth acquisition, and 602, pitch and yaw gyros and gyro electronics for sun acquisition. Both units are required on a one-shot basis which involves only a few minutes. In order to take into account the increase in failure rate during turn-on relative to continuous operation, a time period of one hour was used in computing the probability of success of the acquisition executions. The probability of sun acquisition is

$$P_{SA} = e^{-611.86 \times 16^{-6}} = .9994$$

and the probability of earth acquisition is

$$P_{EA} = e^{-302.23 \times 10^{-6}} = .9997$$

These numbers are sufficiently close to unity so that it can be assumed that successful completion of midcourse maneuver implies successful earth and sun reacquisition. Since the change from the omni to the directional antenna is a direct consequence of earth acquisition, the function also will be assumed to be successfully completed if midcourse maneuver is successful.

The average value for midcourse maneuver is

$$\overline{V}_{MC} = V_{MC}\, P_{MC} = (15.1)(.800) = 12.08 \tag{20}$$

The average value for acquisition, which can be performed whether or not the midcourse maneuver is successful, is

$$\overline{V}_{AQ} = V_{AQ}(P_{MC} + P_{NMC}) = (5.8)(.836) = 4.85 \tag{21}$$

b. Tracking

The evaluation of the contribution of tracking to the average mission value involves the transponder units which are utilized in the tracking function and the units required for general spacecraft operation. This latter category includes power supply, attitude control, thermal control, and the basic CC and S oscillator units, all of which must be operable at any time if tracking is to be performed. Tracking may be accomplished as two-way, which is the preferred mode, or one-way, which can be performed if the phase-locked receiver (803) has failed and the crystal oscillator (805) and bias switch (806) are operable (see Exhibit 13).

The antenna function is to be switched from omni to directional immediately after midcourse maneuver; however, it is assumed that the omni antenna may be used up to 42 days (1008) hours) if necessary. In the first 190 hours only the omni antenna can be used, and after 1008 hours only the directional antenna can be used. Between 190 hours and 1008 hours the two are treated redundantly.

Since the two modes of interest, two-way and one-way tracking, are determined by the condition of the transponder units, the probability equations for these only will be discussed first; subsequently the probability that the other required units are operable will be applied to obtain the over-all probabilities for the two tracking modes during various time periods. Recall that for the time period from 0 to 190 hours only the omni antenna can be used. Hence, the probability of two-way tracking at time t during this period is

$$P_{T2}(t) = \prod_j P_j(t) \tag{22}$$

where J = 802, 803, 807, 808, 810 (unit designations). The probability of being able to perform only one-way tracking during this period is

$$P_{T1}(t) = \left[1 - P_{803}(t)\right] \prod_j P_j(t) \tag{23}$$

where j = 802, 805, 806, 807, 808, 810 .

For the period from 190 to 1008 hours the probabilities are

$$P_{T2}(t) = \prod_j P_j(t) \left\{ \left[1 - (1 - P_{801}(t)P_{809}(t))\right] \left[1 - P_{808}(t)P_{810}(t)\right] \right\} \tag{24}$$

where J = 802, 803, 807 .

$$P_{T1}(t) = \left[\prod_j P_j(t)\left[1 - P_{803}(t)\right]\right] \times$$
$$\left[\left\{\left[1 - (1 - P_{801}(t)P_{809}(t))\right]\left[1 - P_{808}(t)P_{810}(t)\right]\right\}\right] \tag{25}$$

where J = 802, 805, 806, 807 . From 1008 to 2590 the probabilities are

$$P_{T2}(t) = \prod_j P_j(t) \tag{26}$$

where J = 801, 802, 803, 807, 809 and

$$P_{T1}(t) = \left[1 - P_{803}(t)\right] \prod_j P_j(t) \tag{27}$$

where J = 801, 802, 805, 806, 807, 809 .

As was stated earlier, in order to perform tracking in either mode, certain units outside the transponder must be operable. From 0 to 1008 hours, these units are the CC and S transformer-rectifier (401) and oscillator (402), units 501, 502, and 503 in the power supply, units 601, 603, and 604 of the attitude control, and thermal control (901). In addition, the one-shot events such as solar panel erection, sun acquisition, etc., must have been successful. Up to 1008 hours the earth need not have been acquired to obtain tracking value since tracking can be performed with the omni antenna which does not depend upon roll stabilization. Subsequent to 1008 hours, roll stabilization is necessary, requiring units 504 in the power supply and 605, 606, 607 for earth tracking. Although in reality earth acquisition, midcourse maneuver, sun reacquisition, and earth reacquisition are to be executed within a period of several hours it is assumed for simplicity that all are executed at 190 hours. It is further assumed that solar panel erection and sun acquisition take place in the first hour. Then the probability that the spacecraft is operating properly, excluding data and tracking equipment, for the time period from 0 to 190 hours is

$$P_{SC}(t) = P_{SP}P_{SA}\prod_j P_j(t) \tag{28}$$

where P_{SP} = probability of successful solar panel erection

P_{SA} = probability of successful sun acquisition

and j = 401, 402, 501, 502, 503, 601, 603, 604, 901

After 190 hours tracking yields value whether or not midcourse maneuver has been successful. From 190 to 1008 hours the expression for P_{SC} is

$$P_{SC}(t) = (P_{MC} + P_{NMC})\prod_j P_j(t) \tag{29}$$

where j = 401, 402, 501, 503, 601, 603, 604, 901: P_{MC} = probability that the spacecraft performs successfully through midcourse maneuver: and P_{NMC} = probability that the spacecraft performs successfully through 190 hours except that midcourse maneuver fails. Since the units 401, 402, etc., occur in the expressions for P_{MC} and P_{NMC} for the first 190 hours the time variable t is taken from 190 hours. From 1008 to 2590 hours we add units required for roll stabilization, obtaining

$$P_{SC}(t) = P_{MC} + P_{NMC}) \prod_j P_j(t) \tag{30}$$

where j = 401, 402, 501, 502, 503, 601, 603, 604, 901, 504, 606, 608, 605.

Reiterating the earlier discussion, the preferred tracking mode is two-way. If this is not available and one-way tracking can be performed, some value is still accrued (up to 550 hours), but at a decreased rate. The probability of being able to perform in the two-way tracking mode at time t is denoted by $P_{T2}(t)$ and the rate of value accrued at time t for this mode is denoted by $v_{T2}(t)$ (see Exhibit 18). The probability of not being able to perform in the two-way mode, but being able to perform in the one-way mode at time t is denoted by $P_{T1}(t)$ and the value accrual rate by $v_{T1}(t)$. Tracking in either mode also requires those units not associated with the transponder but which are involved in the expression for $P_{SC}(t)$. The average value accrual rate at time t is then determined by the following expression

$$\overline{v}_T(t) = \left[P_{T2}(t)v_{T2}(t) + P_{T1}(t)v_{T1}(k)\right] P_{SC}(t) \tag{31}$$

The probabilities $P_{T2}(t)$, $P_{T1}(t)$ and $P_{SC}(t)$ are tabulated for various times in Exhibit 23. The graph of the average value accrual rate for tracking, $\overline{v}_T(t)$, and the maximum accrual rate, is shown in Exhibit 24. The maximum value accrual rate, which is the rate at which the tracking function accrues values if there are no equipment failures, is equal to $v_{T2}(t)$ since $P_{T2}(t)$ and $P_{SC}(t)$ would be equal to unity in this case and P_{T1} equal to zero.

The integration of $\overline{v}_T(t)$ up to time τ , which represents the average value accrued to that time, is equal to

$$\overline{V}_T(\tau) = \int_0^\tau \overline{v}_T(t)dt \tag{32}$$

EXHIBIT 23 - TABULATION OF PROBABILITIES INVOLVED IN THE TRACKING FUNCTION

Time (hours)	P_{T2}	P_{T1}	P_{SC}
190	.976	.007	.836
550	.933	.048	.774
1800	.778	.138	.269
2590	.696	.185	.184

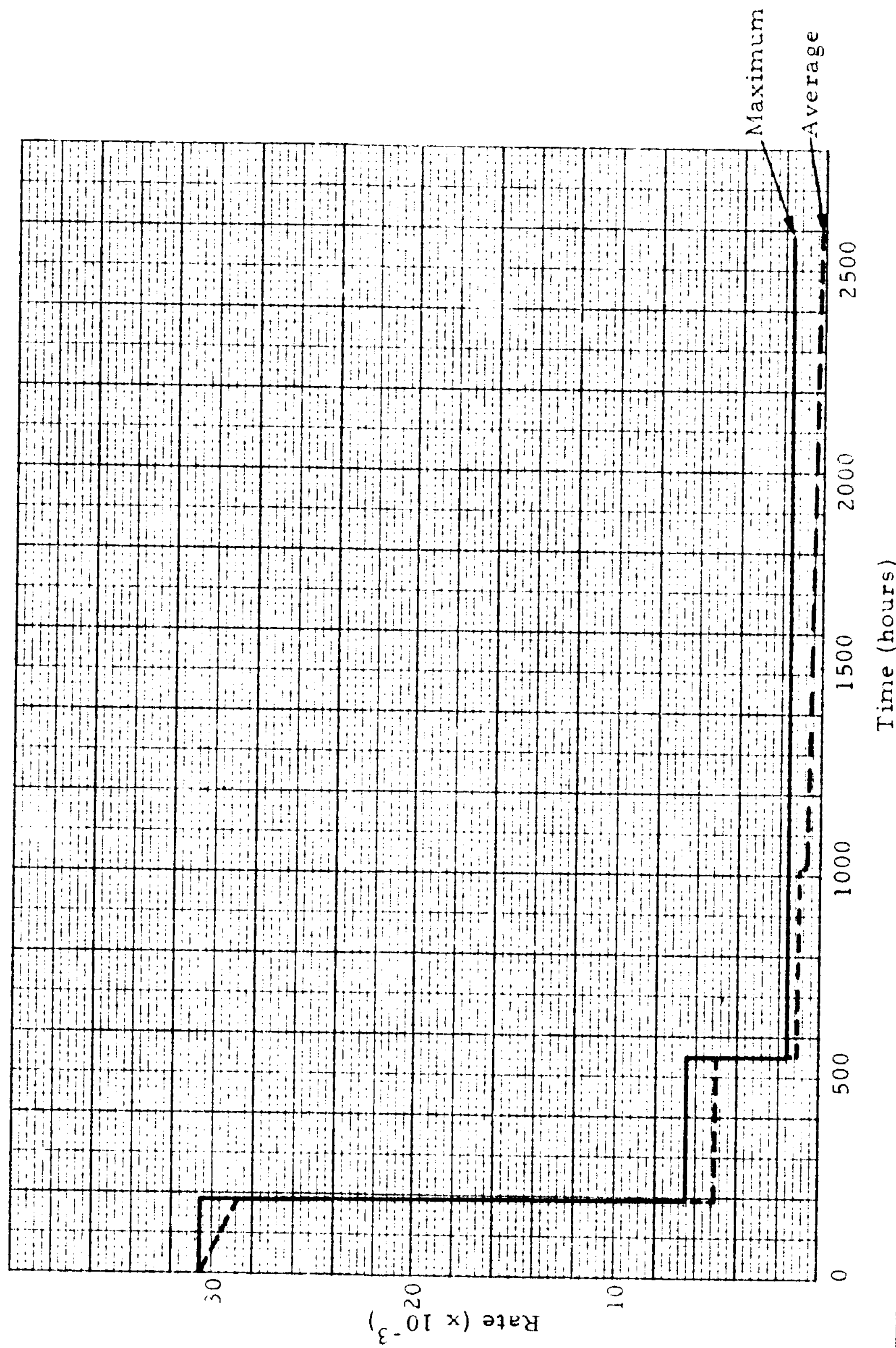

EXHIBIT 24 - TRACKING VALUE ACCRUAL RATE

This is shown in Exhibit 25 along with the maximum accrued value curve. The average value accrued by the tracking function is about 8.76 which is 75 percent of the maximum value of 11.6.

c. Cruise Science Data

This subsection discusses only the science data generated during the cruise phase; the planet science data will be considered later in the section. Referring to the units diagrammed in Exhibit 1, it can be seen that the failure of units 101, 106, 107, 108, or 109 causes loss of all cruise science data, failure of 104 causes loss of the ions and particles data, and loss of 105 causes loss of plasma data and the magnetometer scale. Cruise science data also utilizes the subcarrier generation and modulation units diagrammed in Exhibit 4 and the transponder units diagrammed in Exhibit 13. In addition, the units involved in the expression for $P_{SC}(t)$ must be operable if cruise science data is to be transmitted, since obviously, the spacecraft must be generating power, have attitude control, thermal control, etc., in order to send back any kind of data.

The probability that the subcarrier generation and modulation units required for science data are operable at time t is

$$P_{SGM}(t) = \prod_j P_j(t) \tag{33}$$

where $j = 281, 282, 283, 284, 285, 286, 287, 288, 251$.
As far as the transponder units are concerned, it is assumed that data is successfully transmitted if the equipment is either in the two-way or one-way tracking mode. There is no decrease in data value assigned in the latter mode. In addition to those transponder units required for tracking, the modulator (804) must also be operable in order to transmit data. Thus, the probability of successfully transmitting science data considering only the transponder is

$$P_{DT}(t) = P_{804}(t)\left[P_{T2}(t) + P_{T1}(t)\right] \tag{34}$$

where $P_{T2}(t)$ and $P_{T1}(t)$ are defined by Equations 22 and 27.

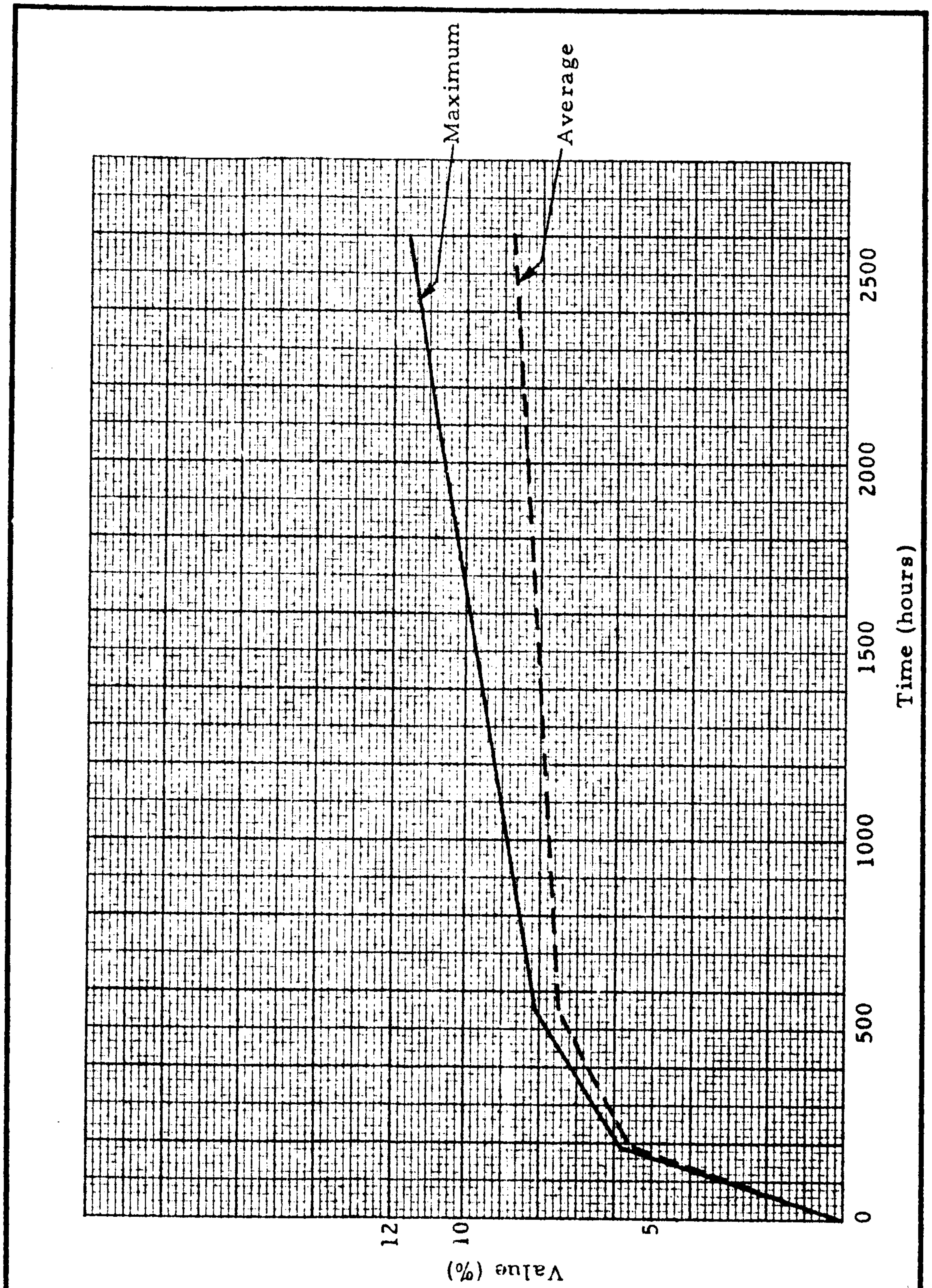

EXHIBIT 25 - TRACKING ACCRUED VALUE

Referring only to the units in Exhibit 1, the probability that all cruise science data can be sent is

$$P_{S1}(t) = \prod_j P_j(t) \tag{35}$$

where $j = 104, 105, 101, 106, 107, 108, 109$. The probability that <u>only</u> the data on ions, particles, cosmic dust, and magnetometer scale can be sent is

$$P_{S2}(t) = (1 - P_{105}(t)) \prod_j P_j(t) \tag{36}$$

where $j = 104, 101, 106, 107, 108, 109$. The probability that only plasma and magnetometer data can be sent is

$$P_{S2}(t) = (1 - P_{104}(t)) \prod_j P_j(t) \tag{37}$$

where $j = 101, 105, 106, 107, 108, 109$.

The value accrual rate for the ions, particles, cosmic dust and magnetometer scale data will be denoted by $v_{S2}(t)$ while the rate for plasma and magnetometer is denoted by $v_{S3}(t)$. The rate for both is simply the sum: $v_{S1}(t) = v_{S2}(t) + v_{S3}(t)$. Then the total average value accrual rate for cruise science data at time t is

$$\bar{v}_S(t) = [P_{S1}(t)v_{S1}(t) + P_{S2}(t)v_{S2}(t) + P_{S3}(t)v_{S3}(t)$$

$$P_{804}(t)\left[P_{T2}(t) + P_{T1}(t)\right] P_{SGM}(t)P_{SC}(t) \tag{38}$$

The probabilities $P_{S1}(t)$, $P_{S2}(t)$, $P_{S3}(t)$, and $P_{SGM}(t)$ are tabulated in Exhibit 26. The other probabilities were presented earlier and the value accrual rates, $v_{S2}(t)$ and $v_{S1}(t)$, are listed in Exhibit 17. Exhibit 27 depicts the graph of the average cruise science data accrual rate, $\bar{v}_S(t)$ The integrals of these curves representing the total cruise science data value accrued to time t are shown in Exhibit 28.

EXHIBIT 26 - TABULATION OF PROBABILITIES INVOLVED IN CRUISE SCIENCE DATA

Time (hours)	P_{S1}	P_{S2}	P_{S3}	P_{SGM}
190	1.000	1.000	1.000	.971
550	.909	.015	.026	.919
1000	.806	.029	.057	.858
1800	.652	.048	.089	.758
2590	.526	.059	.112	.672

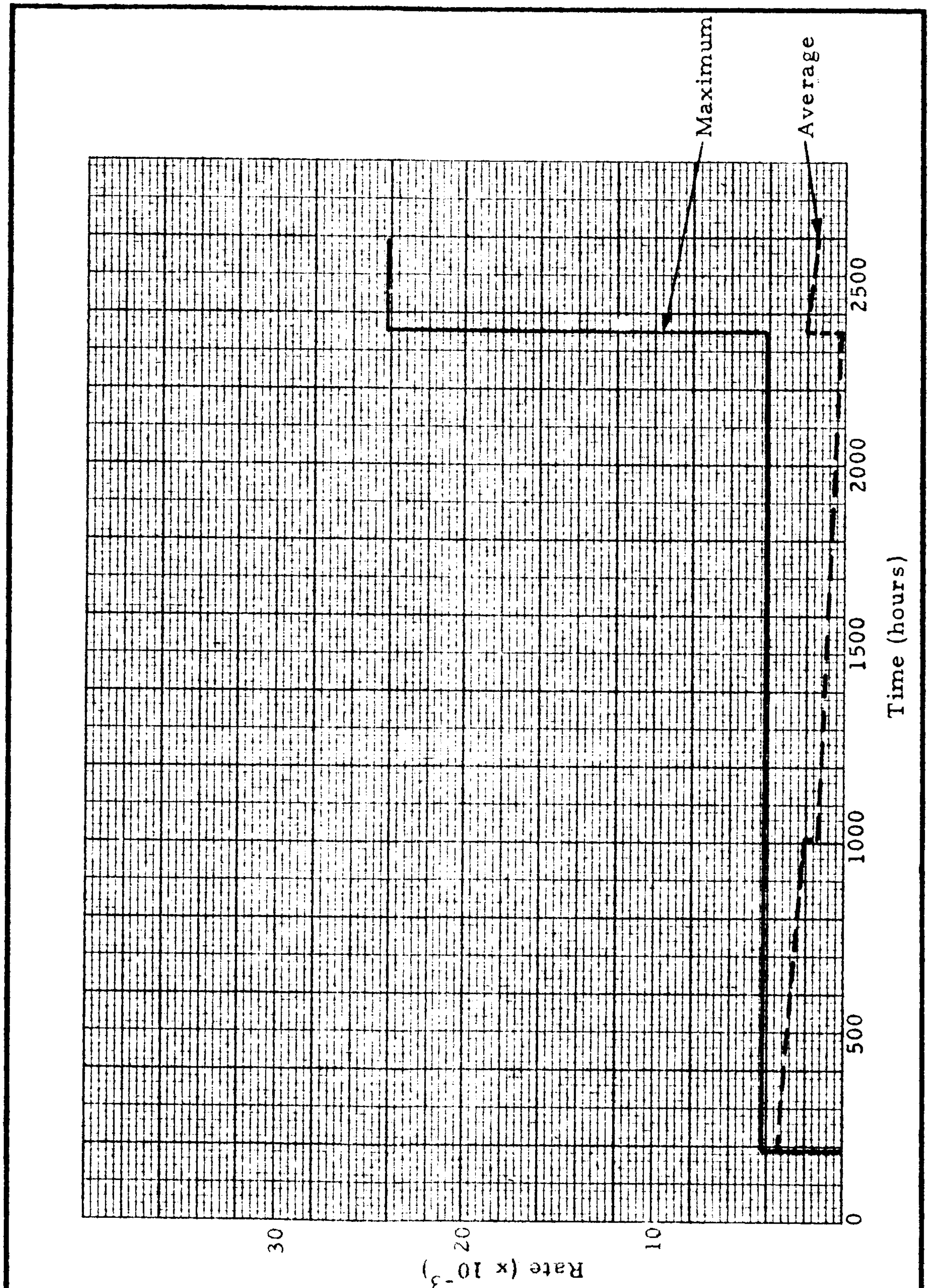

EXHIBIT 27 - CRUISE SCIENCE DATA VALUE ACCRUAL RATE

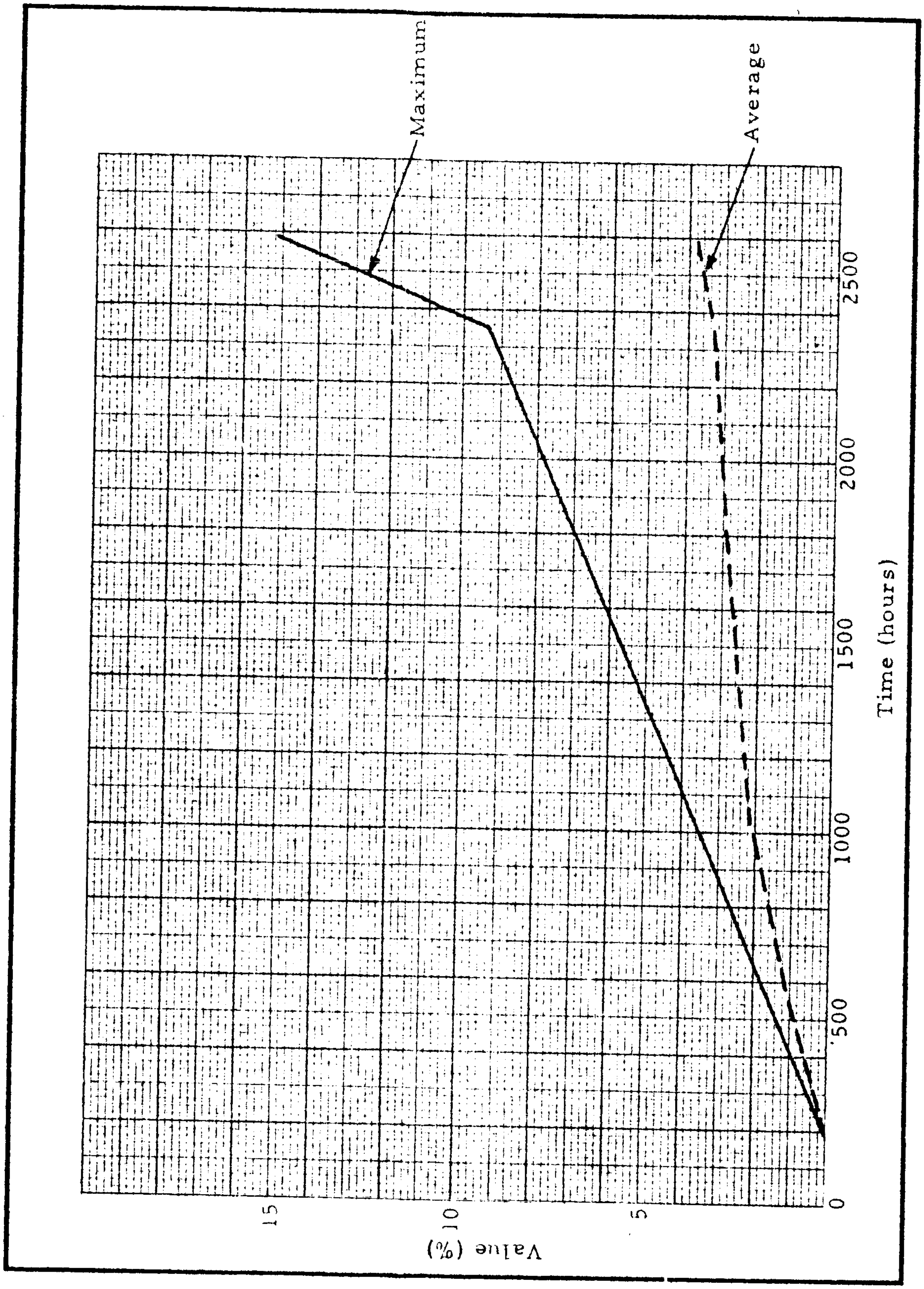

EXHIBIT 28 - CRUISE SCIENCE DATA ACCRUED VALUE

Referring to Exhibit 28, it can be seen that the cruise science data accrues on the average a value of about 3.78 compared to a maximum value of 15.1. Thus, the average mission accrues 25 percent of the desired value for cruise science data.

d. Engineering Data

Referring to Exhibits 2 and 3, it is evident that engineering data permits a much finer gradation of partial values than the other portions of the mission objectives because of the great variety of ways in which data can be lost. For instance, if unit 203A fails, one of the ten E deck words is lost, but if unit 202D fails all E deck words are lost. In the evaluation of engineering data losses, only those units which have a relatively high probability of failure and whose failures result in significant data loss have been included. The units meeting these criteria were, the A to D converter (243) which is common to all words in decks A through F; the low-deck programmer (206), which is common to decks D, E, and F; and the C programmer (208) and A1 switch (242A) which are common to decks C, D, E, and F.

Units 280, 282, 283, 285, 286, 287, 288, and 257 in the subcarrier generation and modulation group are required for all engineering data words. The required transponder units are the same as those necessary for transmission of cruise science data. Similarly, the "spacecraft units" required (those involved in the expression for $P_{SC}(t)$) are naturally the same as in the cruise science data and tracking compositions.

Considering only the engineering data units specified as critical in the previous paragraph, the probability that no data words are lost up to time t is

$$P_{E1}(t) = P_{243}(t)P_{206}(2)P_{208}(t)P_{242}(2) \qquad (39)$$

The probability of losing decks A-F, with the event registers and command monitor still operable, is

$$P_{E2}(2) = 1 - P_{243}(t) \qquad (40)$$

Units 206, 208, and 242 do not enter into this computation since, if unit 243 has failed, decks A-F are lost no matter what condition these units are in. The probability of losing decks D, E, and F and nothing else is

$$P_{E3}(t) = \left[1 - P_{206}(t)\right] P_{243}(t) P_{208}(t) P_{242}(t) \qquad (41)$$

The probability of losing decks C, D, E, and F and nothing else is

$$P_{E4}(t) = \left[1 - P_{208}(t) P_{242}(t)\right] P_{243}(t) \qquad (42)$$

Unit 206 does not enter into the computation since if 208 or 242 is down, decks C-F are lost no matter what the condition of unit 206.

The value accrual rates for engineering data, listed in Exhibit 17, are denoted as follows:

$v_{E1}(t)$ = accrual rate of all engineering words

$v_{E2}(2)$ = accrual rate of event registers and the command monitor

$v_{E3}(3)$ = accrual rate of decks A, B, and C, the event registers, and the command monitor

$v_{E4}(4)$ = accrual rate of decks A and B, event registers, and the command monitor

The average accrual rate for engineering data at time t is

$$\begin{aligned} \bar{v}_E(t) = & \left[P_{E1}(t) v_{E1}(t) + P_{E2}(t) v_{E2}(t) \right. \\ & \left. + P_{E3}(t) + P_{E4}(t) v_{E4}(t)\right] \\ & \times P_{804}(t) \left[P_{T2}(t) + P_{T1}(t)\right] P'_{SGM} P_{S2}(t) \end{aligned} \qquad (43)$$

where P'_{SGM} is equal to P_{SGM} in Equation (38) with unit 280 replacing unit 281. The probabilities $P_{E1}(t)$, $P_{E2}(t)$, $P_{E3}(t)$, and $P_{E4}(t)$ are given for various values of t in Exhibit 29.

The graphs of $\bar{v}_E(t)$ and the maximum accrual rate for engineering data, $v_{E1}(t)$ are presented in Exhibit 30. The total accrued values are shown in Exhibit 31. The average value of accrued engineering data is

EXHIBIT 29 - TABULATION OF PROBABILITIES INVOLVED IN ENGINEERING DATA COMPUTATIONS

Time (hours)	P_{E1}	P_{E2}	P_{E3}	P_{E4}
190	.968	.009	.019	.004
550	.911	.025	.054	.010
1000	.843	.046	.093	.018
1800	.736	.081	.152	.031
2590	.643	.114	.200	.043

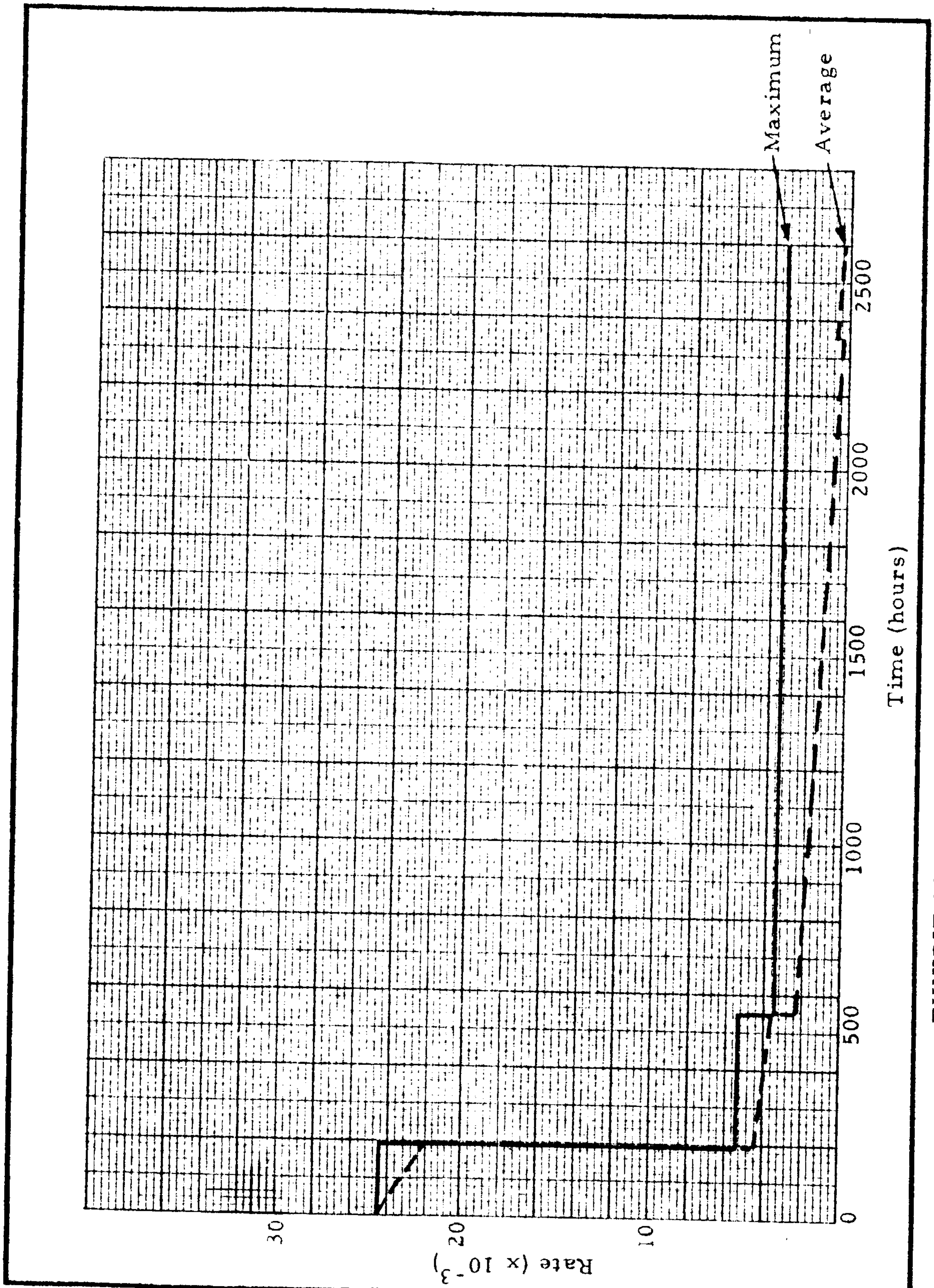

EXHIBIT 30 - ENGINEERING DATA VALUE ACCRUAL RATE

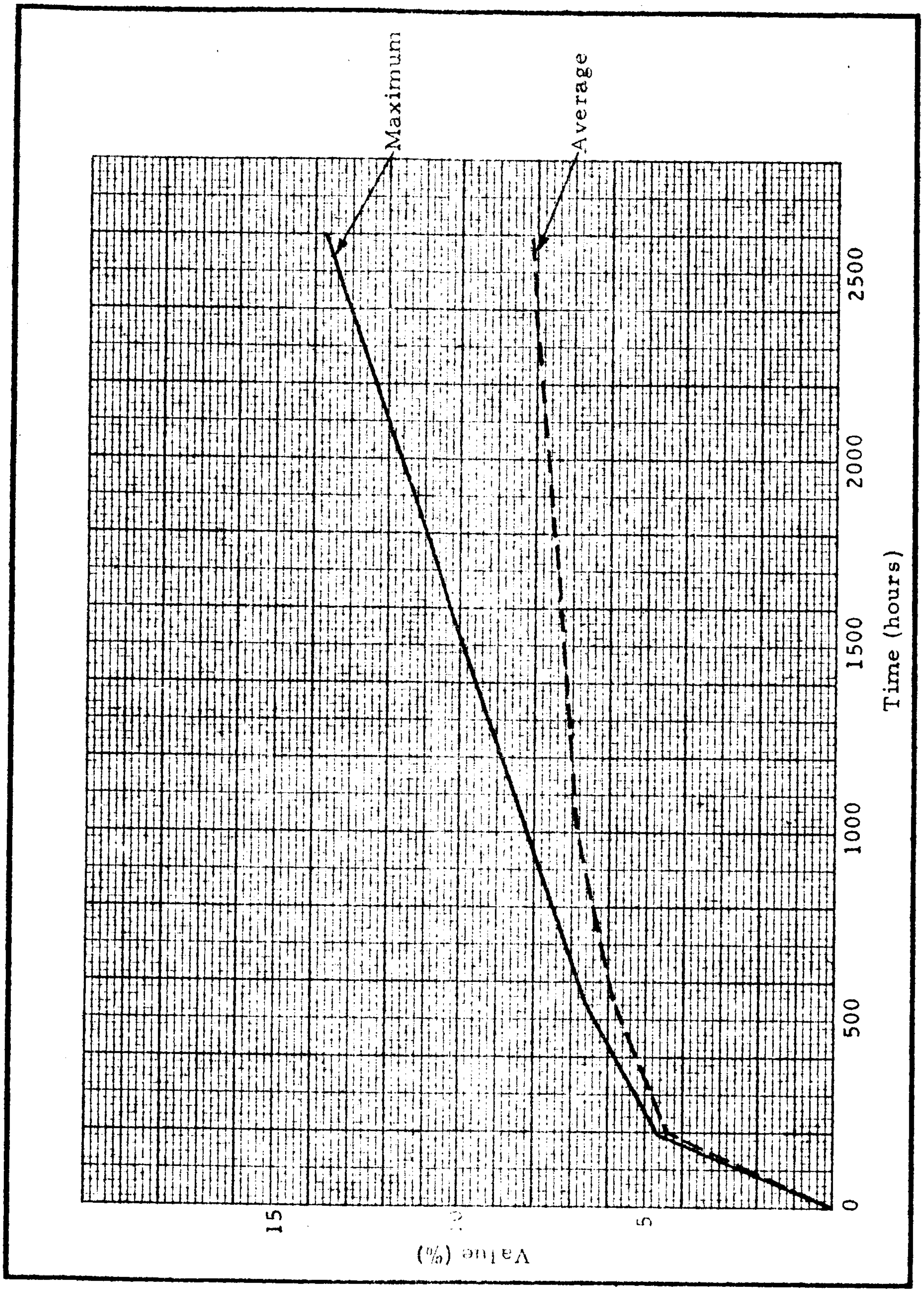

EXHIBIT 31 - ENGINEERING DATA ACCRUED VALUE

8.11 while the maximum is 13.7. Thus the average mission obtains about 59 percent of the designed value for engineering data.

e. Reach Planet Neighborhood with Tracking

In order to reach the planet neighborhood with tracking, the midcourse maneuver must have been successful. The probability of this is denoted by P_{MC} . Next, units 401, 402, 501, 502, 503, 504, 601, 603, 604, 605, 606, 608, and 901 must be operable. These units are exactly the same as those involved in the expression for $P_{SC}(t)$ (see Equation (28)). Finally, it is assumed that the transponder must be able to operate in either the two-way or one-way tracking mode. The probability of reaching the planet neighborhood with tracking is then equal to

$$P_{PN} = P_{MC} P_{SC}(t_1) \left[P_{T2}(t_2) + P_{T1}(t_2) \right] \tag{44}$$

where t_1 is computed from 190 to 2590 hours, since the units in the expression for $P_{SC}(t)$ are also included in P_{MC} for the first 190 hours, and t_2 is equal to 2590 hours.

The value of this event, V_{PN} , is, from Exhibit 17, 9.3. The probabilities are

$$P_{MC} = .80$$

$$P_{SC}(2400) = .22$$

$$P_{T2}(2590) \doteq .70$$

$$P_{T1}(2590) = .18$$

The average value is then

$$\overline{V}_{PN} = P_{PN} V_{PN} = (.158)(9.3) = 1.47 \tag{45}$$

f. Obtain Planet Science Data

To obtain planet science data it is evident that the midcourse maneuver must have been successful. Also, the units required for spacecraft operations and transmission of the data must not have failed during the 2590 hours of the mission. Finally, the signal to activate the planet science experiments must have been successful, either through the CC and S or through ground command. The probability of successful midcourse maneuver (P_{MC}) has already been discussed in a previous subsection. The probability of successful spacecraft operation from the time of midcourse maneuver and operability of required data transmission units involves the following units: 251, 281, 282, 283, 284, 285, 286, 287, 288, 401, 402, 501, 502, 503, 504, 601, 603, 604, 605, 606, 608, 801, 802, 803, 804, 807, 809, and 901. The probability that none have failed by encounter is simply

$$P_{EN} = \prod_j P_j(t_j) \tag{46}$$

where j includes all the above listed units and t_j is the time duration associated with each. The time duration for all units except 801, 804, 807, and 809 is 2400 hours since the expression for P_{MC} includes the reliability of these units for the first 190 hours. P_{MC} includes the reliability of units 801 and 809 for the first 167 hours and does not include units 804 or 807 at all. Thus, t_j for the former two is 2423 hours and for the latter two is is 2590 hours.

The probability of successfully turning on the cruise science mode is equal to the probability that either the appropriate CC and S units or the command units are operable at 2590 hours. This is equal to

$$P_{CO} = 1 - \left[1 - P_{301}(t)P_{302}(t)P_{303}(t)P_{304}(t)P_{312}(t)\right] \times \left[1 - P_{403}(t)P_{406}(t)P_{410}(t)\right] \tag{47}$$

where $t = 2590$ hours.

The probability of obtaining planet science data is then

$$P_{PS} = P_{MC}P_{EN}P_{CO} \tag{48}$$

These probabilities are

$$P_{MC} = .800$$

$$P_{EN} = .108$$

$$P_{CO} = .980$$

$$P_{PS} = .085$$

The assigned value V_{PS} for planet science data is 29.1 The average value, then is

$$\overline{V}_{PS} = P_{PS}V_{PS} = (.085)(29.1) = 2.46 \tag{49}$$

g. Complete Mission

As stated previously, value is accrued during a mission in two ways. Tracking and engineering and cruise science data accrue value over a period of time while value from midcourse maneuver, acquisition, reaching the planet neighborhood with tracking, and returning planet science data are assumed to be accrued at specified times. Exhibit 32 shows the average and maximum value accrual rates for the mission. These curves were generated simply by summing the rates for tracking, engineering data, and cruise science data.

The values contributed by the four one-shot objectives and by the three time-dependent objectives up to encounter are shown in Exhibit 33. The integrations of the curves in Exhibit 32 with the addition of the values of the events listed in Exhibit 33 are graphed in Exhibit 34. The maximum curve, it will be recalled, represents a perfect mission, while the average curve represents the accrual of value for an average mission, theoretically determined over a series of many identically defined missions. In other words, we may interpret Exhibit 34 as indicating that, given the

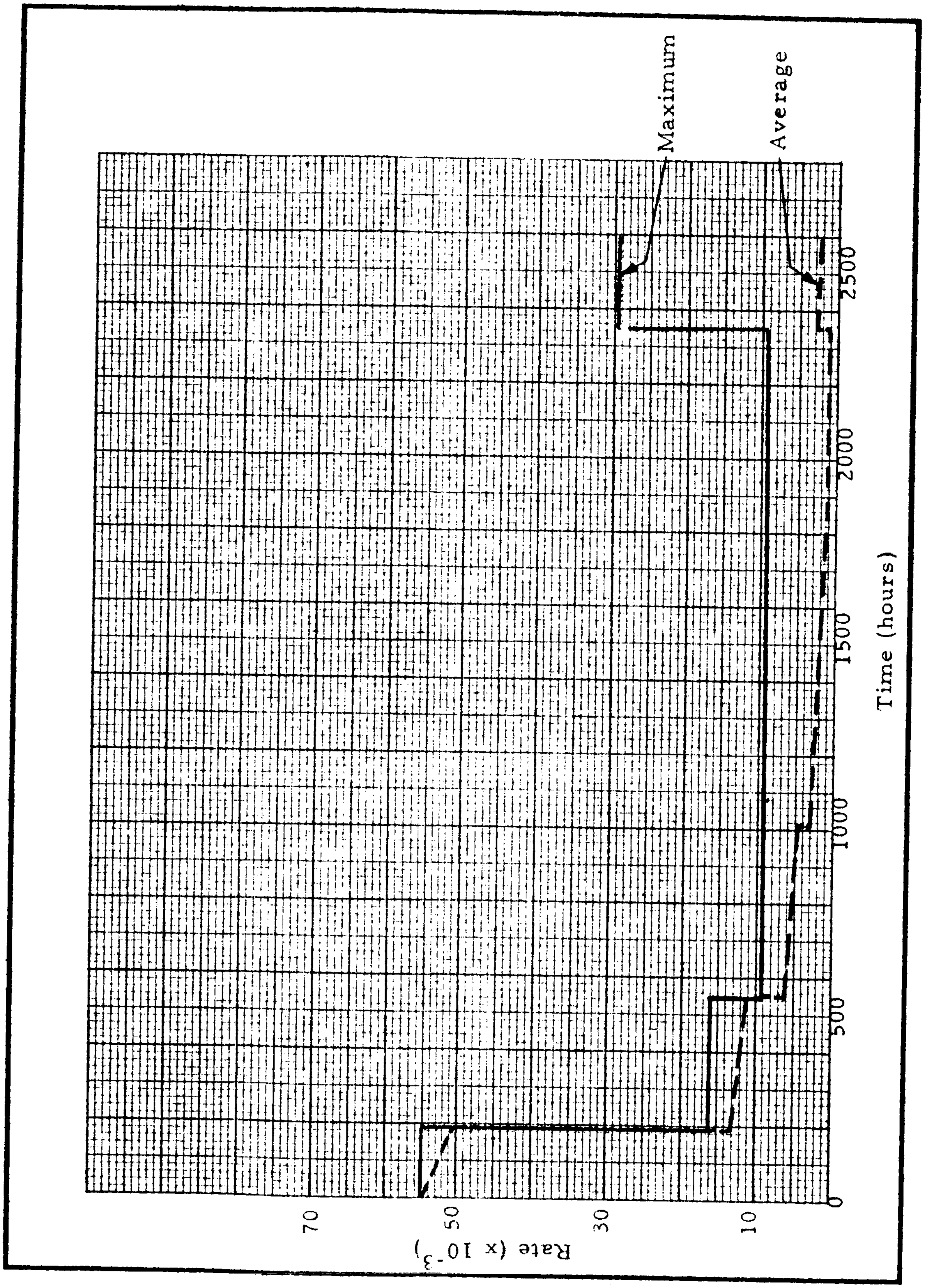

EXHIBIT 32 - MISSION VALUE ACCRUAL RATE

EXHIBIT 33 - ACCRUED VALUES FOR MISSION OBJECTIVES

	Maximum	Average
1. Midcourse maneuver	15.1	12.08
2. Acquisition	5.8	4.85
3. Tracking	11.6	8.76
4. Engineering data	14.0	8.11
5. Cruise science data	15.1	3.78
6. Reach planet neighborhood	9.3	1.47
7. Planet science data	29.1	2.46
Total	100.0	41.51

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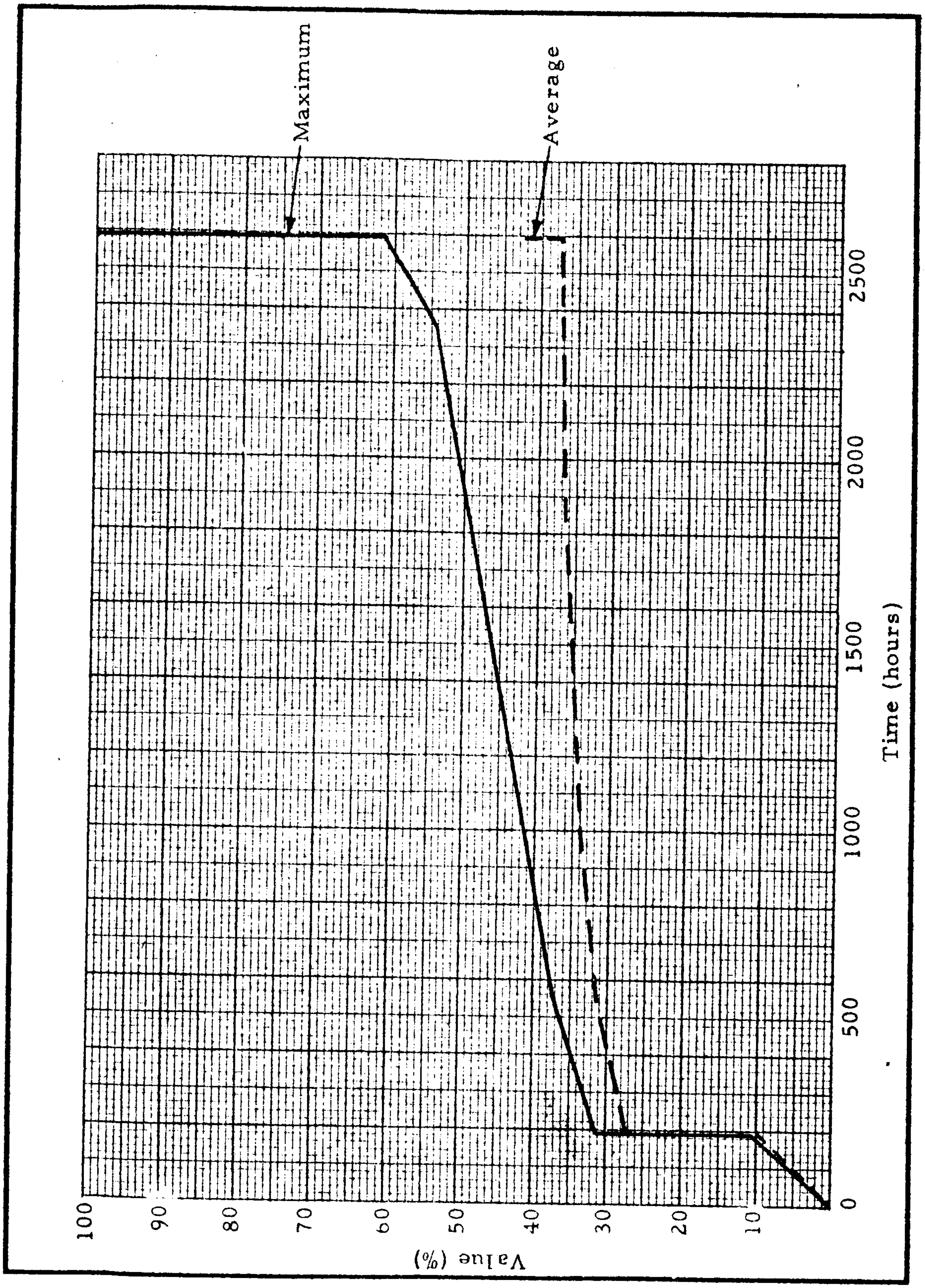

EXHIBIT 34 - MISSION ACCRUED VALUE

assumptions discussed throughout this report, the value accrued by an average mission determined over a totality of many missions which are identical in purpose but which differ stochastically due to equipment failures is equal to 42 percent of the desired value or that value which would accrue if all equipment were functioning properly through encounter.

V. TESTING CONSIDERATIONS

A. Constraints

The following testing considerations and recommendations are made on the basis of a somewhat limited knowledge of the spacecraft. This knowledge is based on a study of the spacecraft design specifications, the circuit diagrams, and the space program studies. The reliability analysis itself has also provided background information relative to the testing recommendations. Application of these recommendations can be made only with due tradeoff considerations with the time, funds, and manpower available, as well as with the test facilities and equipment, and, most important, the available spacecraft hardware. It is possible and even probable that certain of the testing recommendations made here have already been incorporated in the test program.

The principal objective of further testing of the Mariner R spacecraft is assumed to be for the purpose of improving the spacecraft reliability rather than demonstrating functional capability. This objective is particularly important in later missions, since the relative value of events occurring at planetary distances will be higher than with current shots.

B. Test Requirements

The test requirements for future test programs will be formulated from one or more of the following requirement areas. These tests will be necessary to identify selected areas for modification of design and manufacturing processes to attain improved spacecraft reliability.

1. Special problems of a functional nature, such as the existing thermal control problem
2. Generic spacecraft hardware experience with components of a similar nature that are difficult to mechanize
3. Reliability analysis indicating high-failure-rate components or subsystems
4. The continued search for and verification of failure modes and their effects on performance

5. The need to determine general system functional stability and operating capabilities under marginal conditions

C. General Recommendations

Of the variety of useful testing approaches possible, it is recommended that a principal effort be invested in the development or product improvement type of test. The test should consist of functional operation of the spacecraft with superimposed stresses and perturbations to produce an accelerated test. It is further suggested that the techniques of statistical experiment design be employed where possible to improve the data returned for a given amount of testing.

The test plan should consist of a series of compressed-event cycles. The design of the cycle would result from an examination of the principal functional and environmental events that occur during a typical ground sequence and flight mission, the occurrence of these events being compressed in time to evolve a short cycle. It is important that the environment indigenous to these events in the actual situation be simulated to the extent possible during these compressed-event cycles.

A further and important aspect of the test plan should include the use of stresses that exceed those actually encountered where such added stress can, in fact, be traded off with time of operation. Considerable engineering judgment must be used in selecting the type and amount of additional stressing to be applied to the system. Selected perturbations of functional and environmental phenomena are also useful for forcing failure of the weak links in the design. The selection of functional perturbations should be constrained to conditions that have some likelihood of occurrence during the normal mission cycle. This likelihood or probability of occurrence can be combined with the effect of the perturbation to yield quantitative knowledge of the system reliability. The use of stress and of perturbation in general allows the collection of more meaningful data during any given testing period.

The testing schedule would consist of the subjection of the assembled spacecraft system to a continuing series of these compressed-event cycles with, of course, the usual shutdown and failure analysis procedure when failures and instabilities develop. It is desirable that the cycle not be interrupted on a random basis but rather only for scheduled incipient failure searches (or for the occurrence of a failure).

A number of techniques can be used in the search for incipient failures. A particularly interesting possibility consists of utilization of a trend analysis technique with the selection of typical components for removal from the system after which the system is refurbished with new components and put back on test. The removed components can then be tested to determine the performance of characteristic parameters that exhibit a trend toward a failure condition, such as the β and I_{cbo} characteristics of a transistor.

The results of the above test program will provide information not only on catastrophic failure modes but also on the out-of-tolerance or drift failure. The mechanism and the effect of such failures should provide clues to selected redesign in order to minimize the probabilities of their occurrence.

D. Planning Factors

It is desirable to concentrate the stressing and perturbation emphasis in those areas where the results can provide the most useful redesign information. The reliability analysis was examined for those areas of high failure rate that might logically be improved the most with additional performance information. The results of the analysis were most useful in selecting the following subsystems or components that should be stressed or subjected to environmental or functional perturbations during the compressed-event cycle system testing.

1. The science power switching and data conditioning system has a probability of success at encounter of 44 percent. An examination of the reliability units (101 and 109) in the system indicates that a generally high failure rate exists. The system is made up of relay and solid-state digital circuitry, and the following techniques may be employed effectively to identify design weaknesses:

a. Vary input and supply voltages in order to determine operational thresholds for the equipment.

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b. Introduce voltage transients to identify sensitive solid-state components.

c. Apply thermal stress to ascertain marginal cooling situations.

2. An examination of the data encoder reveals a probability of full operation at encounter of only 15 percent. The critical areas in this subsystem are the master counter block, the low-deck programmer, and the A-D converter. The circuitry is similar to that of the science measurement system above, and the stressing techniques would be similar.

3. The attitude control is a particularly pertinent subject for investigation, since it is required throughout the mission, and its probability of operation at encounter is only 31 percent. The two principal problem areas are the earth sensor and gate and the antenna servo drive and hinge. These are, respectively, optic and electromechanical systems combined with solid-state analog circuitry. Stressing techniques include application of abnormal electrical stress to circuits and the use of marginal optical signals to the earth sensor and perturbing torques to the hinge drive.

4. The transponder has a better probability of success at encounter (68 percent); however, the phase-locked receiver is a difficult mechanization problem generically and has been reported as having threshold difficulties in actual operation. Stressing techniques would include carrier signal perturbation at near-threshold levels and the introduction of noise (such as that generated internally from a degraded mixer) in addition to the normal galactic background noise.

Other considerations that would have a bearing on the design of the compressed-event cycles and the stressing of equipment during these cycles must include the spacecraft environment. The importance of subjecting the spacecraft system to an engineering simulation of the actual environments that it encounters during the normal mission events cannot be overemphasized. It is recognized, however, that in this area, equipment and facilities restrictions are often quite severe. If it is impossible to combine thermal-vacuum and vibration environments concurrently with the functional events, it is at least necessary to subject the system to these environments on a sequential basis. Both thermal and vibration environments offer excellent possibilities for stressing the system as a tradeoff with operating time.

The Mariner R specifications provide that ground-handling will not result in loads on the spacecraft that exceed those encountered in flight. It is observed that no formal shock limits are proposed for the flight regime, and as a result it must be inferred that the ground-handling equipment must limit shock loads to those of allowable continuous acceleration in flight. It is generally impractical to design shock isolation equipment to limit the transmission to these acceleration levels, so it is suggested that ground-handling of the spacecraft may induce shock loads considerably above those for which it is designed. It is desirable to instrument a ground-handling sequence to determine the character of shock sustained by this spacecraft and to simulate these shocks in the compressed-event cycles. Such tests may reveal the desirabliity for ground-handling equipment redesign or more likely, procedural changes. It is considered most important to instrument all prime flight hardware shipments during all handling sequences so that all preflight shock loads may be revealed. It becomes, of course, a problem of engineering judgment to determine the disposition of a flight spacecraft that has been subjected to high shock loadings. It is not possible to make very meaningful judgments on this matter in the general case.

E. Other Test Possibilities

A number of other useful testing possibilities exist in the Mariner R program and should be utilized as appropriate. For example, thorough functional verification of all design changes is always recommended. The subtleties of such changes often induce unexpected side effects which can seriously affect performance and reliability. The thermal control problem that exists on the present flight vehicle certainly indicated that added emphasis in thermal testing using the thermal control model might pay off. It is suggested that these tests be run with as close an approximation of the solar input spectrum as possible, from the standpoint of both intensity and spectral distribution. Mechanisms for the degradation of both the passive and active surfaces should be hypothesized and simulated where possible.

The use of marginal testing may be effectively applied to the operation of the pyrotechnics. In this instance, marginal currents would be applied to determine the threshold of operation of pyrotechnic devices. The probability of occurrence of such marginal currents that cause failure of the pyrotechnics can be used to infer knowledge of the probability of failure of the pyrotechnic-initiated functions. If this probability is sufficiently high, it may be desirable to initiate redesign to reduce same.

Two acceptance testing techniques are recommended as standard procedure. The first of these is the burn-in process combined with aging, as appropriate, to minimize the failure rate of electronic components. The mechanism, of course, is to reduce the infant mortality rate and to approach more positively the regime of constant failure rate. A number of extenuating circumstances are discussed in subsection F. The other acceptance technique is that of the superclean or "LOX-clean" process applied to parts and assemblies of plumbing systems. Experience with hot and cold gas plumbing systems has indicated the desirability of attending to this detail in achieving maximum functional reliability for valves and other kinematic components of such systems.

A final technique of checkout testing should be considered, particularly if a long life for a given type space vehicle is anticipated. Long life here refers to the number of vehicles launched as well as calendar life. The technique is known as trend testing and might be appropriately applied to the attitude control system of the Mariner vehicle. The attitude control system is essentially analog in nature and should contain a number of indicative parameters that exhibit characteristic trends toward failure with operating time. If the generic failure trend of these parameters is known, a short period of their life can be examined prior to launch with very accurate testing techniques to determine whether the parameters are on an appropriate degradation curve, or whether they will tend out of limits at the observed rate before the end of the mission. The technique is useful in predicting the performance reliability from a trending out-of-tolerance or a drifting degradation point of view of analog systems. This technique represents the only known testing technique which can contribute meaningful information at the time of launch for predicting the probable life of a particular operating system.

F. Test Termination Point

In all development programs the question of when to stop testing is invariably raised with respect to some aspect of the development. If the hardware being tested is earmarked for no other purpose, the answer is usually based on the economic considerations of the cost of the testing against the potential return in additional experience. The recommendations of the preceding discussion are based on the assumed availability of such "test" hardware. The question takes on a different complexion, however, when the hardware being tested is actually intended for ultimate operational use.

The problem involved can be discussed by reference to Exhibit 35 Here a typical launch preparation sequence is diagrammed with the ultimate goal to launch during a given window. In tracing the sequence back in time from the launch window, a certain period is necessary for actual mating of the spacecraft and a final checkout prior to launch. Line 7 provides for a launch site assembly and test period which is preceded by a shipping period. Prior to shipping, a period is allowed as a maintenance cushion, this period being necessary to effect the repair of the most difficult to maintain failure that could occur prior to this time and still allow time for the subsequent elements of the sequence.

The problem arises now as a result of a completed in-house testing program as designated in line 1 and a successful functional performance verification as indicated by line 2. It assumes the form of a question as to what extent testing should be continued during the period before the beginning of the maintenance cushion. A general answer to this question is not within the purview of this discussion, if in fact it is possible. Certain adjuncts to the decision process for a specific situation, however, can be considered.

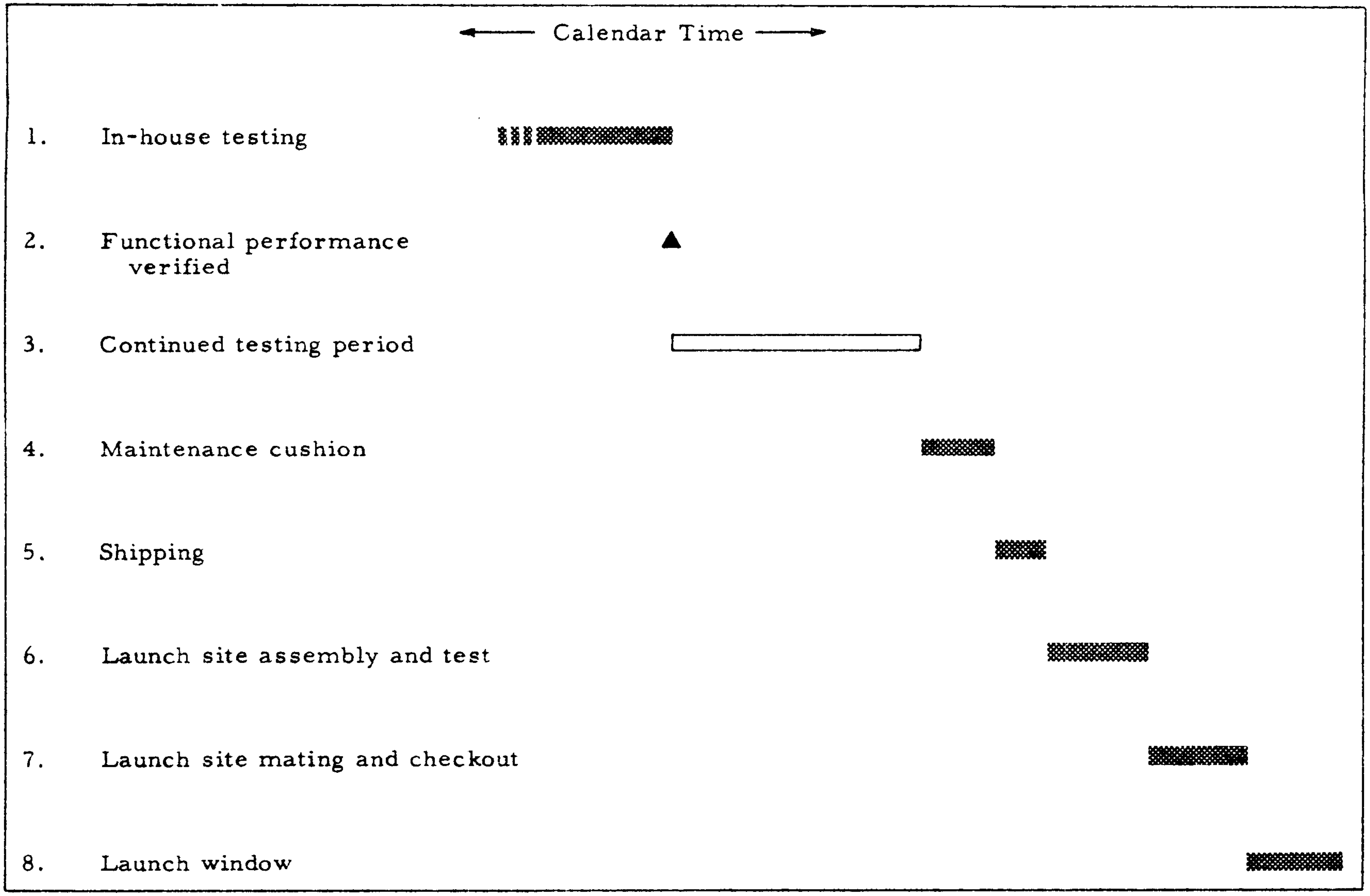


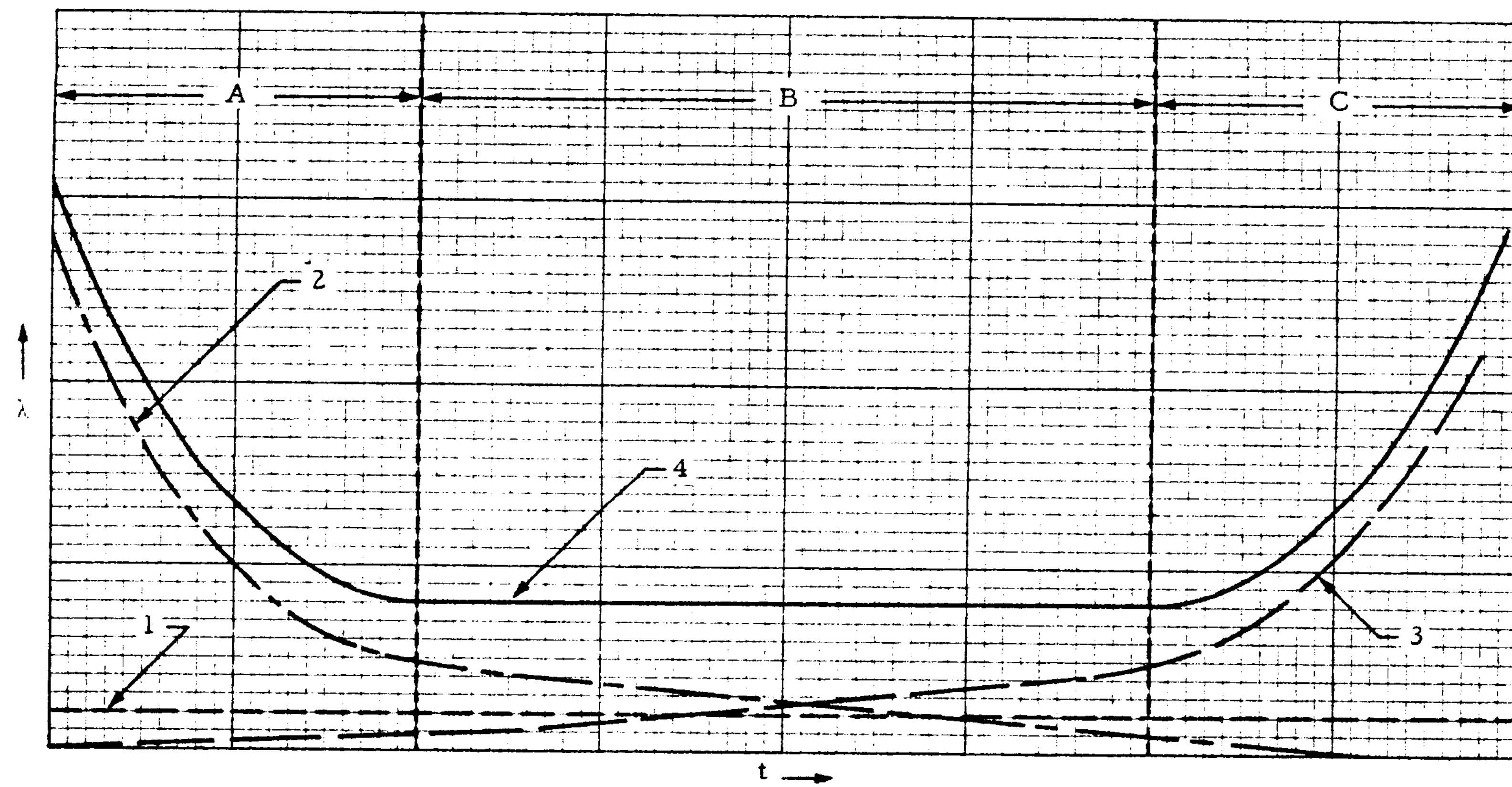
EXHIBIT 35 - LAUNCH PREPARATION SEQUENCE

Exhibit 36 depicts a typical "bathtub" failure rate curve and hypothesizes the fundamentals of which it may be composed. Curve 2 characterizes the failure rates attributable to flaws in either materials or workmanship wherein high failure rates occur early in time and gradually decay as time increases. Curve number 3 indicates a characteristic of wear-out which early in time would be low but would increase with time. These curves are characteristic of the Weibull distributions with beta factors less than unity and greater than unity, respectively.

A further contribution to the total failure characteristic curve 4 is given by curve 1, which assumes a constant failure rate for the collected effect of failures due to rare causes. This corresponds to the Weibull curve characteristic of beta = unity. The predominant contribution to the failure rate in region A is that due to infant failures or flaw-type failures from curve 2. Conversely, in region C the failure rates are predominantly derived from wear-out considerations. The composite failure rate in region B is approximately constant with decreasing contribution from flaws and an increasing contribution from wear-outs which balance.

In the general case it is desirable to operate equipment during its useful mission in region B, the region of low, constant failure rate as described by curve 4. Upon reaching the point of satisfactory performance of the system and being relatively assured of operation within region B, the decision on continuing to test should be negative. This is true for any equipment exhibiting wear-out characteristics such as those containing thermionic devices, electromechanical components, or any parts wherein degradation of a physical or functional parameter occurs with time of operation.

If the equipment involved, however, does <u>not</u> exhibit a wear-out characteristic, but rather exhibits a characteristic similar to curve (2) a continuation of testing would result in a further reduction of failure rates. This is precisely the situation that may exist with solid-state logic circuitry operating in a benign environment and under very low stress. In this case, increasing operation time would result in a lower expected failure rate during the mission. It is important to note, however, that if testing is continued, adequate preparation for a failure must be made.



1: Collected rare occurrence failure causes
2: Flaw failures
3: Wear-out failures
4: Total failure rate

A: High flaw (infant) failure regime
B: "Constant" failure rate regime
C: High wear-out failure regime

EXHIBIT 36 - FAILURE RATE REGIMES

The implication is that maintenance time must be available to correct the failure and that a replacement part or unit must be available with sufficient time of operation behind it to have reduced the failure rates to the level attained by the operational system at the time the decision to continue the testing was made. Otherwise, the flight test schedule may force a flight using operational equipment of a higher failure rate than existed at the time of decision.

In short, after satisfactory functioning has been verified on a given flight vehicle, only the solid-state digital circuitry exhibiting decreasing failure rates with time should continue on test and then only if spare equipment exists, with comparable operating time on it, with which to maintain failures that occur. It is possible that such operating subsystems can be identified in the Mariner R spacecraft which are also, in fact, discretely maintainable assemblies. Likely candidates would be the data encoder, the CC and S, and the Science Data Conditioning Subsystem.

In the (unlikely) situation where a great deal of calendar time exists between the termination of testing and the beginning of the maintenance cushion period, a period of confidence testing should be instituted just prior to the maintenance cushion. During the dormant period, complete isolation of the spacecraft from mechanical or thermal environment excursions is very important.

VI. CONCLUSIONS AND RECOMMENDATIONS

One of the principal tasks of this evaluation has been the formulation of a set of recommendations regarding a testing philosophy adapted as closely as possible to the current needs of the Mariner program. These considerations have been set forth in Section V of this report and will not be restated here. As a general comment, it can be said that testing provides a basis for confidence in the reliability estimates of the various subsystems of the spacecraft, and, although the connection appears to be somewhat tenuous at times, an optimized testing program should be organized and vigorously prosecuted. Systematized data recording should be made an essential part of that program so that results can be disseminated and applied in future work.

During this assessment, the examination of documents on subsystem circuitry and hardware design was necessarily limited to that required for the indentification of reliability units which would account for the most obvious failure modes. Consequently, a critical design review of specific circuits and devices could not be undertaken, and recommendations at this lower level of detail cannot be attempted. The major conclusions resulting from the study are, therefore, rather general, although they can be taken as indicative of the results that would be possible if more detailed engineering assessments were made of the spacecraft subsystems.

A. Conclusions Regarding Subsystems

1. Power Supply

Power supply reliability is not as high as is desirable for a function of such importance. The complexity of the booster regulator indicates a possible need for re-examination of this concept of power conversion and inversion. Step reconfiguration of the solar arrays, combined with some shunt regulation of the array output, might be accomplished with a net gain in reliability (although this might require that the inverters be capable of handling a wider range of input voltage).

2. Transponder

Both the concept and resultant reliability appear to mark this subsystem as one of the stronger design areas of the spacecraft. The redundancy of the standby oscillator tends to preserve many of the functions of this important device. A means for using the capability of the omnidirectional cavity at encounter distances should be sought.

3. Data Encoder

This appears to be a weak subsystem, reliability-wise; however, many of the potential failure modes are of a degraded rather than a catastrophic type. The effects of the large number of piece parts can be softened by the use of specially selected components with proven low failure rates. The commutator programmers, consisting of long strings of flip-flops, might provide an area for reliability improvement. The use of fewer flip-flops and the addition of logical gating circuitry to activate the switches might reduce the over-all failure rate, but it is not known whether other constraints force this apparently excessive use of transistors.

4. Science Measurements

The Science Data Conditioning System represents a certain degree of functional duplication from a reliability standpoint, in that some of the data encoder functions are repeated in it. This offers a degree of operational independence which, while it apparently lowers the classical reliability of the spacecraft, actually improves the expected mission value. The power switching scheme should be analyzed using sequential-switching algebra techniques to ascertain whether or not the logical operations are indeed being accomplished with the greatest economy of relays and contacts.

5. Ground Commands

The reliability estimate of this subsystem appears to be somewhat low, but this must be interpreted in the light of the difficulties in mechanizing this function. A failure of this subsystem is viewed in the study as resulting in the inability to receive and execute transmitted commands; however, it is recognized that inadvertant or incorrect command execution is a potentially greater hazard. This has evidently been alleviated at the cost of complexity in the detector, and this complexity is not considered to be a design weakness.

6. Central Computer and Sequencer

The time scale for the performance of the majority of the functions of this device is relatively short (190 hours), and its reliability for this period seems satisfactorily high. The single function of signalling planet encounter could be made more reliable by the use of at least a redundant oscillator, or by some other means of duplicating the long-period clock function. Consideration should be given to a standby clock.

7. Altitude Control

The difficulties attendant upon implementing the maintenance of stability in four degrees of freedom make it tempting to review the need for specifying this mode of operation. It is concluded, however, that the payoff resulting from a fully stabilized spacecraft is sufficiently high to warrant efforts to overcome the design difficulties associated with it. Most of these difficulties appear to be tied to the earth tracking function, and any review of subsystem design should be directed to the devices most directly involved in this function; these are identified as the earth sensor and control and the antenna hinge and servo. The employment of derived rate stabilization to reduce the duty cycle on the gyros is a significant design strength from the reliability standpoint.

B. General Recommendations

These recommendations, of a very general nature, can readily apply to programs other than Mariner; however, they have been arrived at by means of the observations made during the course of this assessment.

1. Continue to assess spacecraft reliability and use the results in all stages of design and fabrication.

2. Examine complex subsystem design for reliability by quantitative rather than intuitive methods. Despite the necessity for making approximations and assumptions, the resulting numerical estimates offer a better basis for relative evaluation of designs than mere "guesses" or adherence to vague concepts of good design practice.

3. Restudy the system as an entity to determine whether overall reliability requirements can be realistically apportioned. This will lead to more confidence in any decisions to emphasize reliability of one subsystem at the cost of some functional capability of other subsystems.

4. Use the figure-of-merit and accrued value concept to assess mission objectives. It is concluded, on the basis of this study, that the Mariner R project is not excessively ambitious, in that it has (from a very approximate point of view) nearly a 50-percent chance of being a completely sucessful mission. Future changes, however, should probably be undertaken for the purposes of design simplification and reliability improvement rather than for the accomplishment of more difficult objectives.

APPENDIX A

APPENDIX A

RELIABILITY UNIT PARTS COUNT

The piece-parts count for each reliability unit used in the assessment of the Mariner spacecraft is listed on the following pages. Excluding those portions of the spacecraft that were not assessed (such as the scientific experiments and the engineering measurement transducers), there are more than 14,000 separate component parts involved in this study. It is believed that these have been accounted for to a high degree of accuracy, although small errors in denumeration are quite likely to exist. Of possibly more concern is the small, but almost certain, occurrence of errors in the classification and identification of some types of parts. This type of error arises from the necessity for making assumptions regarding part identification.

Within the compressed time schedule of this first-level study, it was not possible to obtain and audit complete sets of assembly drawings and parts lists; information of this type could not be made available within the allotted time except for certain subsystems. Schematic diagrams and block diagrams of all subsystems were provided by the Systems Design Section of JPL and these represent the most important type of documentation required for an analysis of this type. Nevertheless, a parts count based on a schematic diagram is subject to some inaccuracies in that part identification is generally not completely given on such documents. For example, the distinction between film resistors and wire-wound resistors is not often made on schematic diagrams, and must be gleaned from available catalog information or assumed on some rational basis. Similar comments apply to general-purpose diodes and zener diodes as well as to tantalytic and other types of capacitors.

The parts-count tabulation can be used to recognize the causes for the assignment of high failure rates to specific units. It will be observed that complexity can be related to the number of piece parts, as well as to the configuration of the parts, and any effort to improve reliability will benefit from a study of the unit parts counts given here. To facilitate this kind of analysis, the failure rate for each unit is shown, together with individual component failure rates. All rates shown have been multiplied by a factor of 1×10^6 .

Unit	Number of Components	Individual Component Failure Rate[1]
101: Relays		
Relays	3	.60
Diodes	3	.15
	6	2.25
102: Scan Logic and Relays		
Capacitors	21	.01
Diodes, silicon	116	.15
Transistors	39	.30
Resistors, composition	140	.01
	316	30.71
103: Relays		
Relays	5	.60
Diodes	2	.15
	7	3.30
104: D-D Converter		
Capacitors	35	.01
Diodes, silicon	415	.15
Transistors	51	.30
Resistors, composition	232	.01
	733	80.22
105: A-D Converter		
Capacitors	19	.01
Diodes, silicon	112	.15
Transistors	85	.30
Resistors, composition	172	.01
	388	44.21
106: Shift Register, P/N Generator, Buffer		
Capacitors	44	.01
Diodes, silicon	191	.15
Transistors	45	.30
Resistors, composition	193	.01
	473	44.52

[1] Failure rate given is to be multiplied by 10^{-6}. Unit is "per hour" unless otherwise noted.

Unit	Numbers of Components	Individual Component Failure Rate
107: Timer and Subframer		
Capacitors	52	.01
Diodes, silicon	230	.15
Transistors	80	.30
Resistors, composition	254	.01
	616	61.56
108: 200-Hour Check Relays		
Capacitors	17	.01
Diodes, silicon	78	.15
Transistors	32	.30
Resistors, composition	105	.01
	232	22.52
109: Science T/R		
Capacitors	12	.01
Diodes, silicon	32	.15
Transistors	15	.30
Resistors, composition	45	.01
Chokes	6	.20
Transformer	1	2.00
	111	13.07
201A, B, C: L/L Switch		
Capacitors	5	.01
Diode, silicon	1	.15
Transistors	3	.30
Transformer	1	2.00
Resistors, composition	8	.01
	18	3.18
202A, B, C: C Switch		
Capacitors	2	.01
Diode, silicon	1	.15
Transistors	2	.30
Transformer	1	2.00
Resistors, composition	4	.01
	10	2.81

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Unit	Number of Components	Individual Component Failure Rate
203A, B, C, · · · , J: L/L Switch		
Same as 201A		
202D: C Switch		
Same as 202A		
204A, · · · , I: L/L Switch		
Same as 201A		
202E: C Switch		
Same as 202A		
205A, · · · , I: D Switch		
Capacitors	4	.01
Diode, silicon	1	.15
Transistors	3	.30
Transformer	1	2.00
Resistors, composition	8	.01
	17	3.17
202F: C Switch		
Same as 202A		
206: Low-Deck Programmer		
Capacitors	28	.01
Diodes	216	.15
Transistors	8	.30
Resistors, composition	30	.01
Resistors, film, signal	32	.23
Resistors, wirewound	60	1.03
	374	104.54

Unit	Number of Components	Individual Component Failure Rate
207: L/L		
Capacitors	12	.01
Capacitors, tantalum	8	.08
Diodes, silicon	2	.15
Inductor	1	.20
Transistors	13	.30
Transformers	4	2.00
Resistors, composition	32	.01
	72	13.48
208: C Programmers (Shift Register)		
Capacitors	76	.01
Diodes, silicon	38	.15
Transistors	29	.30
Resistors, composition	116	.01
	259	16.32
241A, · · · , I: Isolated Power Supply		
Capacitor	1	.01
Capacitor, tantalum	1	.08
Diodes, silicon	2	.15
Diode, zener	1	.26
Transistor	1	.30
Transformer	1	2.00
Relay	1	.60
Potentiometer	1	1.08
Resistors, film, signal	4	.23
	13	5.55

242A: A1 Switch

Same as 202A

242B, · · · , J: A or B Deck Switch, 9 High-Rate Words

Same as 202A

242K, · · · , R: A or B Deck Switch, 7 High-Rate Words

Same as 202A

Unit		Number of Components	Individual Component Failure Rate
243:	A to D Converter		
	Capacitors	82	.01
	Capacitors, tantalum	5	.08
	Diodes, silicon	127	.15
	Inductor	1	.20
	Transistors	74	.30
	Transformer	1	2.00
	Resistors, composition	238	.01
		528	47.05
244:	Event Register No. 1		
	Capacitors	22	.01
	Diodes, silicon	31	.15
	Transistors	8	.30
	Transformer	1	2.00
	Resistors, composition	42	.01
		104	9.69
245:	Event Register No. 2		
	Capacitors	22	.01
	Diodes, silicon	31	.15
	Transistors	8	.30
	Transformer	1	2.00
	Resistors, composition	42	.01
		104	9.69
246:	Event Register No. 3		
	Capacitors	19	.01
	Diodes, silicon	31	.15
	Transistors	8	.30
	Resistor, composition	39	.01
		97	7.63
247:	Event Register No. 4		
	Capacitors	20	.01
	Diodes, silicon	35	.15
	Transistors	43	.30
	Resistors, composition	8	.01
		106	18.43

Unit	Number of Components	Individual Component Failure Rate
248: Event Sequencer		
Capacitors	8	.01
Diodes, silicon	11	.15
Transistors	5	.30
Resistors, composition	17	.01
	41	3.40
249: Transfer Register		
Capacitors	90	.01
Diodes, silicon	70	.15
Transistors	46	.30
Resistors, composition	178	.01
	384	26.98
250: BO F/F		
Capacitors	4	.01
Diodes, silicon	2	.15
Transistors	2	.30
Resistors, composition	7	.01
	15	1.01
251: T/R		
Capacitors	6	.01
Capacitors, tantalum	11	.08
Diodes	14	.15
Diodes, zener	15	.26
Inductor	2	.20
Transistor	18	.30
Transformers	2	2.00
Potentiometers	2	1.08
Resistors	36	.23
	106	27.18
252: Command Monitor		
Capacitors	77	.01
Diodes, silicon	70	.15
Diodes, power	6	.01
Transistors	55	.30

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Unit		Number of Components	Individual Component Failure Rate
252:	Command Monitor (Continued)		
	Resistors, composition	38	.01
	Resistors, film, power	35	1.08
	Transformers	6	2.00
		287	78.01
280:	Mode Logic and Transfer, Engineering		
	Diodes, silicon	13	.15[1]
	Transistors	2	.30
	Relays	2	.60
	Resistors, composition	5	.01
		22	3.00
281:	Mode Logic and Transfer, science		
	Diodes	13	.15[1]
	Transistors	2	.30
	Relays	2	.60
	Resistors	5	.01
		22	3.20
282:	Data Modulator		
	Capacitors, tantalum	4	.08
	Diodes, silicon	2	.15
	Transistors	8	.30
	Resistors, composition	30	.01
	Thermistor	1	.30
		45	3.62
283:	Master Counter, Decks A/B Programmer, 24-Word Timer		
	Capacitors	309	.01
	Capacitor, tantalum	1	.08
	Diodes, silicon	271	.15
	Transistors	140	.30

[1] The 13 diodes are arranged such that 4 parallel pairs are in series with the remaining 5. The 13 diodes of unit 281, however, are arranged with 3 parallel pairs in series with the remaining 7.

Unit	Number of Components	Individual Component Failure Rate
283: Master Counter, Decks A/B Programmer, 24-Word Timer (Cont.)		
Relays	2	.60
Resistors, composition	559	.01
	1282	92.61
284: Sync Modulator		
Capacitor	1	.01
Diodes, silicon	6	.15
Transistors	4	.30
Resistors, composition	14	.01
	25	2.25
285: Mixer		
Capacitor, tantalum	1	.08
Transistor	1	.30
Potentiometer	1	1.08
Resistors, composition	4	.01
	7	1.50
286: Subcarrier Generation		
Capacitors	27	.01
Diodes, silicon	10	.15
Transistors	14	.30
Relay	1	.60
Resistors, composition	48	.01
	100	7.05
287: P/N Generator		
Capacitors	27	.01
Diodes, silicon	63	.15
Transistors	17	.30
Resistors, composition	50	.01
	157	15.42
288: Isolated Amplifier		
Transistors	2	.30
Resistors, composition	4	.01
	6	0.64

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Unit	Number of Components	Individual Component Failure Rate
301: T/R		
Capacitors, tantalum	4	.08
Diodes, silicon	6	.01
Inductors	2	.20
Resistors, composition	4	.01
Transformers	2	2.00
	18	4.82
302: Command Detector		
Capacitors	109	.01
Capacitors, tantalum	19	.08
Diodes, silicon	96	.01
Diode, zener	1	.26
Transistors	79	.30
Resistors, film, signal	131	.23
Resistors, composition	166	.01
Transformers	6	2.00
	607	71.32
303: Programmer Logic and Counter		
Capacitors	59	.01
Diodes, signal	61	.15
Diode, power	1	.01
Transistors	33	.30
Resistors, film, signal	35	.23
Resistors, composition	85	.01
Transformer	1	2.00
	275	30.55
304: Address Register		
Capacitors	36	.01
Diodes, signal	24	.15
Transistors	36	.30
Resistors, film, signal	12	.23
Resistors, composition	72	.01
	180	18.24

Unit	Number of Components	Individual Component Failure Rate
305: S.C. Routing and Logic		
Capacitors	10	.01
Capacitor, tantalum	1	.40
Diodes, silicon	17	.15
Diodes, power	6	.01
Transistors	12	.30
Resistors, film, signal	14	.23
Resistors, composition	18	.01
Transformers	3	2.00
	81	16.11
306, ···, 315; 317 RTC, Gate and Switch No. 1, ···, 10; 12		
Capacitor	1	.01
Capacitor, tantalum	1	.40
Diodes, silicon	7	.15
Diodes, power	4	.01
Transistors	2	.30
Resistors, film, signal	2	.23
Resistors, composition	2	.01
Transformer	1	2.00
	20	4.58
316: RTC, Gate and Switch No. 11		
Capacitor	1	.01
Diodes, silicon	7	.15
Diode, power	1	.01
Transistor	3	.30
Resistors, film, signal	3	.23
Resistors, composition	3	.01
Transformer	1	2.00
	19	4.69
401: T/R		
Capacitors	2	.01
Capacitor, tantalum	1	.08
Diodes, silicon	20	.15
Choke	1	.20
Transformer	1	2.00
Resistors, film, signal	5	.23
	30	6.45

Unit		Number of Components	Individual Component Failure Rate
402:	Oscillator and 1-PPM Counter		
	Capacitors	60	.01
	Capacitor, tantalum	1	.08
	Diodes, silicon	52	.15
	Transistors	56	.30
	Cores	30	
	Transformer	1	2.00
	Crystal	1	1.00
	Resistors, film, signal	200	.23
		401	74.28
403:	Magnetic Countdown 1/1500		
	Diodes, silicon	3	.15
	Transistors	12	.30
	Cores	27	
	Resistors, film, signal	39	.23
		81	13.02
404:	Magnetic Countdown 1/50		
	Capacitors	2	.01
	Diodes, silicon	10	.15
	Transistors	9	.30
	Cores	16	
	Relay	1	.60
	Resistors, film, signal	34	.23
		72	12.64
405:	Launch Matrix		
	Capacitors	2	.01
	Diodes, silicon	19	.15
	Transistors	12	.30
	Cores	12	
	Resistors, film, signal	16	.23
		61	10.15
406:	Magnetic Countdown 1/2000		
	Capacitor	1	.01
	Diodes, silicon	5	.15
	Transistors	15	.30
	Cores	31	
	Resistors, film, signal	48	.23
		100	16.30

Unit	Number of Components	Individual Component Failure Rate
407: Driver		
Capacitor	1	.01
Capacitor, tantalum	1	.08
Diodes, silicon	5	.15
Transistors	2	.30
Relay	1	.60
Resistors, film, signal	7	.23
	17	3.65
408: Driver		
Capacitor	1	.01
Diodes, silicon	5	.15
Transistors	2	.30
Relay	1	.60
Resistors, film, signal	7	.23
	16	3.57
409: Driver		
Same as 408		
410: Driver		
Capacitors	2	.01
Diodes, silicon	4	.15
Transistors	2	.30
Relay	1	.60
Resistors, film, signal	8	.23
	17	3.66
411: Driver		
Capacitors	3	.01
Diodes, silicon	4	.15
Transistors	2	.30
Relay	1	.60
Cores	2	
Resistors, film, signal	10	.23
	22	4.13

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Unit	Number of Components	Individual Component Failure Rate
412: S.C. Decoder		
Capacitors	22	.01
Capacitors, tantalum	2	.08
Diodes, silicon	103	.15
Transistors	32	.30
Resistors, film, signal	156	.23
	315	61.31
413: S.C. Registers		
Capacitors	44	.01
Diodes, silicon	199	.15
Diodes, zener	3	.26
Transistors	39	.30
Cores	72	
Resistors, film, signal	183	.23
	540	84.86
414: Timing and Logic		
Capacitors	5	.01
Capacitors, tantalum	2	.08
Diodes, silicon	36	.15
Diodes, zener	2	.26
Transistors	27	.30
Cores	32	
Relay	1	.60
Choke	1	.20
Resistors, film, signal	65	.23
	171	29.98
415: Drivers and Switches		
Capacitors	4	.01
Capacitors, tantalum	17	.08
Diodes, silicon	54	.15
Transistors	20	.30
Relays	3	.60
Resistors, film, signal	77	.23
	175	35.01

Unit	Number of Components	Individual Component Failure Rate
501: Solar Array and Battery		
Capacitor	1	.01
Capacitors, tantalum	2	.08
Diodes, silicon	2	.15
Diodes, zener	5	.26
Transistors	7	.30
Transformers	4	2.00
Relays	3	.60
Resistors, wirewound	10	1.03
Battery cells	18	.75
Solar panels[1]		
	52	37.70
Pyrotechnics		
Relays	8	.60
Transistors	3	.30
Diodes, silicon	6	.01
Capacitors	6	.01
Resistors, composition	21	.01
Latches	6	.02
Squibs	12	106.00
Hinges	4	.02
Actuators, spring	2	1.05
	68	Probability of deployment[2] = .999397
502: Booster Regulator		
Capacitors	19	.01
Capacitors, tantalum	13	.08
Diodes, silicon	17	.15
Diodes, zener	9	.26
Transistors	26	.30
Inductors	4	.20
Transformers	4	2.00
Resistors, film	12	.23
Resistors, composition	48	.01

[1] For discussion of no failure rate estimate, see subsection IV. A. 1.

[2] Method of obtaining this probability follows the list of units.

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Unit		Number of Components	Individual Component Failure Rate
502:	Booster Regulator (Continued)		
	Resistors, wirewound	4	1.03
	Potentiometer	1	1.08
		157	31.16
503:	2.4-kc Inverter		
	Capacitors, tantalum	2	.08
	Transistors	4	.30
	Inductor	1	.20
	Transformers	3	2.00
	Resistors, wirewound	3	1.03
	Resistor, composition	1	.01
	Chokes	2	.20
		16	11.06
504:	400-cps Inverter		
	Capacitors	11	.01
	Capacitors, tantalum	6	.08
	Diodes, silicon	11	.15
	Diode, zener	1	.26
	Transistors	13	.30
	Inductors	5	.20
	Transformers	3	2.00
	Relays, contact	3	.60
	Resistors, composition	32	.01
	Resistors, wirewound	5	1.03
		90	20.67
505:	Two 400-cps Inverters		
	Capacitors	8	.01
	Capacitor, tantalum	1	.08
	Diodes	9	.15
	Transistors	12	.30
	Inductors	2	.20
	Transformers	6	2.00
	Relays, coil	2	.60
	Resistors, composition	10	.01
	Resistors, wirewound	6	1.03
		56	24.99

Unit		Number of Components	Individual Component Failure Rate
601:	Sun Sensors and Sun Gate		
	Capacitor	1	.01
	Diodes, silicon	2	.15
	Diode, zener	1	.26
	Transistors	2	.30
	Resistors, composition	4	.01
	Cadmium sulfide cells	6	.38
		16	3.49
602:	Pitch and Yaw Gyros; Gyro Electronics		
	Capacitors	34	.01
	Capacitors, tantalum	3	.08
	Diodes, silicon	21	.15
	Diodes, zener	10	.26
	Transistors	16	.30
	Resistors, composition	47	.01
	Resistors, film, signal	2	.23
	Inductors	3	.20
	Transformers	5	2.00
	Relays	2	.60
	Rate gyros	2	294.00
		145	611.86
603:	Celestial Relays K1-K4, K5-K6		
	Capacitors	4	.01
	Capacitors, tantalum	4	.08
	Diodes, silicon	13	.15
	Diodes, zener	4	.26
	Resistors, composition	5	.01
	Transformers	3	2.00
	Relays	4	.60
		37	11.80
604:	P and Y Amplifiers, Valves, and Nozzles		
	Nitrogen pressure regulator	1	4.40C[1]
	Capacitors	10	.01
	Capacitors, tantalum	6	.08
	Diodes, silicon	30	.15
	Diodes, zener	5	.26
	Transistors	9	.30

[1] C = cycles.

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Unit	Number of Components	Individual Component Failure Rate
604: P and Y Amplifiers, Valves, and Nozzles (Continued)		
Resistors, composition	44	.01
Transformers	3	2.00
Valves and nozzles	6	.18
	114	23.28
605: Antenna Servo Drive and Hinge		
Capacitors	16	.01
Capacitors, tantalum	8	.08
Diodes, silicon	35	.15
Transistors	2	.30
Resistor, film power	1	1.08
Resistors, film, signal	3	.23
Resistors, composition	24	.01
Transformers	6	2.00
Inductors	2	.20
Rectifiers	6	1.20
Potentiometers	4	1.08
Motor with gear and brake	1	16.00
Relays	2	.60
Servo motor	1	15.00
Clutch, slip	1	3.00
Wormshaft	2	4.00
Gears	2	1.20
Gear, helical	1	.50
Gear, compound	1	6.30
Gear, anti-backlash	1	9.00
Gears, spur	4	6.30
Pinion	1	1.20
Bearing	1	5.00
Bearings, ball	11	9.00
Joint, rotary coaxial	1	75.00
	137	299.38
606: Earth Sensor and Gate		
Capacitors	59	.01
Capacitors, tantalum	34	.08
Diodes, silicon	103	.15
Diodes, zener	23	.26
Transistors	46	.30
Resistors, film, power	5	1.08
Resistors, film, signal	4	.23
Resistors, composition	192	.01

Unit		Number of Components	Individual Component Failure Rate
606:	Earth Sensor and Gate (Continued)		
	Thermistor	1	.30
	Relays	4	.60
	Transformers	16	2.00
	Inductors	3	.20
	Photo multiplier tube	1	3.80
		491	85.88
607:	Roll Gyro and Electronics		
	Capacitors	9	.01
	Diodes, silicon	8	.15
	Diodes, zener	2	.26
	Transistors	6	.30
	Resistor, film, signal	1	.23
	Resistors, composition	19	.01
	Inductor	1	.20
	Transformers	2	2.00
	Rate gyro	1	294.00
		49	302.23
608:	Roll Amplifier, Valves, and Nozzles		
	Capacitors	9	.01
	Capacitors, tantalum	6	.08
	Diodes, silicon	20	.15
	Diodes, zener	5	.26
	Transistors	8	.30
	Resistors, composition	30	.01
	Transformers	2	.02
	Valves and nozzles	4	.18
		84	8.33
701:	Gyro Capacitors and Accelerometer and Electronics		
	Capacitors	38	.01
	Diodes, silicon	24	.15
	Diodes, zener	6	.26
	Transistors	26	.30
	Resistors, wirewound, accurate	5	1.03
	Resistors, film, signal	11	.23
	Resistors, composition	61	.01
	Transformer	1	2.00

Unit	Number of Components	Individual Component Failure Rate
701: Gyro Capacitors and Accelerometer and Electronics (Continued)		
Relays	6	.60
Rectifier	2	1.20
Thermistor	1	.30
Accelerometer	1	28.00
	182	57.93
702: Autopilot Electronics and Servos		
Capacitors	12	.01
Capacitors, tantalum	8	.08
Diodes, silicon	8	.15
Diodes, zener	12	.26
Transformers	23	2.00
Resistors, composition	65	.01
Potentiometers	2	1.08
Torque motors	4	15.00
	134	113.89
703: Propulsion System and Pyrotechnics		
Engine, rocket (thrust chamber)	1	2.00C[1]
Valve, ignition cartridge	1	106.00A[2]
Valve, nitrogen	1	106.00A
Valve, propellant (start)	1	106.00A
Valve, propellant (shutoff)	1	106.00A
Tank and bladder, propellant	1	200.00C
Regulator, nitrogen	1	4.40C
Servo motors	4	15.00
Jet vanes	4	
Valve, shutoff, nitrogen	1	
	16	690.40
Pyrotechnics		
Capacitors	2	.01
Resistors, composition	4	.01
Transistors	2	.30
Relays	8	.60
	16	Probability of deployment = .9999

[1] C = cycles.

[2] A = actuations.

Unit	Number of Components	Individual Component Failure Rate
801: Transfer Relay		
Diodes	7	.15
Resistors, composition	2	.01
Relay	1	.60
	10	1.67
802: T/R		
Capacitors	21	.01
Diodes, silicon	26	.15
Resistors, composition	19	.01
Transistors	12	.30
Transformer	1	2.00
Choke	1	.20
Relay	1	.60
	81	10.70
803: Phase-Locked Receiver		
Capacitors	256	.01
Diodes, silicon	11	.15
Resistors, film, signal	2	.23
Resistors, composition	195	.01
Transistors	42	.30
Transformers	33	2.00
Chokes	27	.20
Crystal	1	.30
Cavity	1	.20
	568	91.12
804: Modulator		
Capacitors	4	.01
Diodes, silicon	1	.15
Resistors, composition	5	.01
Inductor	1	.20
Varicap	2	.30
	13	1.04
805: XTAL Oscillator		
Capacitors	6	.01
Diodes, zener	1	.26

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Unit	Number of Components	Individual Component Failure Rate
805: XTAL Oscillator (Continued)		
Transistor	1	.30
Resistors, composition	7	.01
Transformer	1	2.00
Crystal	1	.30
	17	2.99
806: Bias Switch		
Capacitors	3	.01
Resistors, composition	8	.01
Transistors	2	.30
	13	.71
807: Multiplier, Driver		
Capacitors	46	.01
Diodes, silicon	6	.15
Resistors, composition	35	.01
Transistors	9	.30
Transformers	4	2.00
Chokes	15	.20
Klystron	1	10.00
Cavity	1	.20
	117	25.67
808: Transfer Relay		
Same as 801		
809: Directional Cavity		
Capacitors	4	.01
Resistor, composition	1	.01
Chokes	4	.20
Klystron	1	10.00
	10	10.85
810: Omni Cavity		
Capacitors	4	.01
Resistor, composition	1	.01

Unit	Number of Components	Individual Component Failure Rate
810: Omni Cavity (Continued)		
Chokes	4	.20
Klystron	1	10.00
	10	10.85
901: Thermal Control		
Louvers	9	
Bimetallic actuators	9	.40
Bearings	18	.40
	36	17.00[1]

Two of the above units, 501 and 703, have pyrotechnic portions whose probability of successful operation will be developed here. The failure-rate estimate for unit 901 is also given in detail, since it depends on the number of louvers sticking open or closed.

Pyrotechnic Portion of Unit 501

It is clear from Exhibit 15 that the probability, P(SP), that the solar panels will deploy is

$$P(SP) = P(L_f) \cdot P(H)^4 \, P(SA)^2$$

where $P(L_f)$ = probability that the latches operate

$P(H)$ = probability that each hinge will not fail

$P(SA)$ = probability that each spring actuator will operate

But the probability that a latch will operate is not only dependent on its failure rate, but also on the failure rates of the two associated redundant squibs and of two relay systems. Let L_n be the probability that the latch and its redundant squibs operate:

[1] Computation follows list of units.

$$L_1 = P(\ell_1)\left\{1 - \left[1 - P(S_1)\right]\left[1 - P(S_7)\right]\right\}$$
$$\vdots$$
$$L_6 = P(\ell_6)\left\{1 - \left[1 - P(S_6)\right]\left[1 - P(S_{12})\right]\right\}$$

where $P(\ell_n)$ = probability that latch alone will work

Now, letting R_1 and R_2 designate the relay systems,

$P(L_n/R_1, R_2)$ = probability that the latches and squibs operate, given both R_1 and R_2 operate

$P(L_n/R_2)$ = probability that the latches and squibs operate, given R_1 down

$P(L_n/R_1)$ = probability that the latches and squibs operate, given R_2 down

where $P(L_n/R_1, R_2) = P(R_1)\, P(R_2)\, L_1 \cdots L_6 \qquad n = 1 \cdots 6$

$$P(L_n/R_2) = P(R_2) \quad 1 - P(R_1) \quad P(\ell_1)P(S_2) \cdots P(\ell_6)P(S_{12})$$

$$P(L_n/R_1) = P(R_1) \quad 1 - P(R_2) \quad P(\ell_1)P(S_1) \cdots P(\ell_6)P(S_6)$$

Then the probability of deployment of the solar panels is

$$P(SP) = P(L_n/R_1R_2) + P(L_n/R_2) + P(L_n/R_1) \cdot P(H)^4 \cdot P(SA)^2 \qquad (1)$$

To calculate this probability we need the following failure rate estimates:

	$\lambda \times 10^{-6}$
Latch	.02 Actuations
Squib	106.00 Actuations
Hinge	.02 Actuations
Spring Actuator	1.05 Actuations
R_1	3.11 Hours
R_2	3.76 Hours

where R_1 is composed of

4 Relays
1 Transistor
2 Capacitors
2 Diodes
9 Resistors

R_2 is composed of

4 Relays
2 Transistors
4 Diodes
12 Resistors
4 Capacitors

Substituting

$$L_1 = e^{-.02 \times 10^{-6}} \left\{ 1 - \left[1 - e^{.000106} \right]^2 \right\}$$

$$= .9999$$

$$P(R_1) = e^{-3.11 \times 10^{-6}}$$

$$P(R_2) = e^{-3.76 \times 10^{-6}}$$

$$P(L_n/R_1, R_2) = \left(.9999 \right) \left(e^{-3.11 \times 10^{-6}} \right) \left(e^{-3.76 \times 10^{-6}} \right)^6$$

$$= .999392 \qquad (2)$$

$$P(L_n/R_2) = \left(e^{-3.76 \times 10^{-6}} \right) \left(1 - e^{-3.11 \times 10^{-6}} \right)$$

$$\cdot \left[\left(e^{-.02 \times 10^{-6}} \right) \left(e^{-106 \times 10^{-6}} \right) \right]$$

$$= .000003 \qquad (3)$$

$$P(L_n/R_1) = \left(e^{-3.11 \times 10^{-6}} \right) \left(1 - e^{-3.76 \times 10^{-6}} \right) \left(.9999 \right)^6$$

$$= .000004 \qquad (4)$$

Substituting these in (1) , probability of deployment,

$$P(SP) = (.999392 + .000003 + .000004)\left(e^{-.02\times 10^{-6}}\right)^4\left(e^{-1.05\times 10^{-6}}\right)^2$$
$$= .999397$$

Pyrotechnics of Unit 703

For the purposes of this development, we will define six subunits to unit 703 as follows:

1. Units 1 and 2, parallel units of two relays each, and whose successful operation means N_2 pressure is on.
2. Units 3 and 4, parallel units, whose successful operation provides both fuel and oxidizer.

   The component count for unit 3 is

   2 Relays
   1 Transistor
   2 Resistors, composition
   1 Capacitor

   and the component count for unit 4 is

   2 Relays
   1 Transistor
   2 Resistors, composition
   1 Capacitor
3. Units 5 and 6, parallel units of two relays each, whose successful completion is N_2 pressure off and fuel off.

The failure rates of these subunits, then, are

	$\lambda \times 10^{-6}$	
Unit 1	1.20	
Unit 2	1.20	
Unit 3	1.53	(5)
Unit 4	1.53	
Unit 5	1.20	
Unit 6	1.20	

The probability, $P(703p)$, that the pyrotechnics of unit 703 are successfully operated is

$$P(703p) = \left[1 - \left[1 - P(\text{unit }1)\right]\left[1 - P(\text{unit }2)\right]\right] \cdot \left[1 - \left[1 - P(\text{unit }3)\right]\left[1 - P(\text{unit }4)\right]\right] \cdot \left[1 - \left[1 - P(\text{unit }5)\right]\left[1 - P(\text{unit }6)\right]\right] \quad (6)$$

Substituting (5) in (6) gives

$$P(703p) = .999999$$

<u>Failure Rate Estimate of Unit 901</u>

The unit is composed of

9 Louvers
9 Bimetallic actuators
18 Bearings

The louvers have zero failure rate after injection, but any bearing or actuator can stick a louver; therefore, using the failure rates for these two components given above, we can say

$$P(\text{one louver sticks}) = e^{-1.2 \times 10^{-6}}$$

By definition, the unit fails if two or more louvers stick open or if two or more sitck closed. First, calculate the probability, $P(1\ell_o)$, of exactly one louver sticking open:

$$P(1\ell_o) = \left[1 - e^{-1.2 \times 10^{-6}}\right]\left[e^{-1.2 \times 10^{-6}}\right]^8$$

Next, the probability, $P(9\ell_c)$, that all nine are stuck closed, is

$$P(9\ell_c) = \left(e^{-1.2 \times 10^{-6}}\right)^9$$

So that the probability, $P(2, \cdots, 9\ell_o)$, that two or more are stuck open, is given by

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$$P(2, \cdots, 9\ell_o) = 1 - \left\{ \left[e^{-1.2 \times 10^{-6}} \right]^9 + 9 \left[1 - e^{-1.2 \times 10^{-6}} \right] \left[e^{-1.2 \times 10^{-6}} \right]^8 \right\} \quad (7)$$

and, similarly, the probability that two or more are closed,

$$P(2, \cdots, 9\ell_c) = 1 \left\{ \left[e^{-1.2 \times 10^{-6}} \right]^9 + 9 \left[1 - e^{-1.2 \times 10^{-6}} \right] \left[e^{-1.2 \times 10^{-6}} \right]^8 \right\} \quad (8)$$

Therefore, the probability, $P(901f)$, of failure for unit 901 is given by

$$P(901f) = P(2, \cdots, 9\ell_o) + P(2, \cdots, 9\ell_c) \quad (9)$$

and the probability of its not failing

$$P(901) = 1 - P(901f)$$

$$P(901) = .9999834$$

But this is for 1 hour, so that

$$P(901) = .9999834 = e^{-\lambda}$$

where

$$\lambda = 17.0 \times 10^{-6}$$

APPENDIX B

APPENDIX B

FAILURE RATE SOURCES

1. Introduction

It is of interest to pursue in some detail the background research resulting in specific conclusions concerning the failure-rate estimates used in this assessment, especially the high-population parts, capacitors, resistors, diodes, and transistors. It is clear that these four components dominate the reliability computations and motivate the intensive study of all available sources for a decision on their failure estimates. However, PRC continues to study additional sources of failure-rate data on all parts, and adjusts its estimates whenever new data are available that materially change the background against which the estimates were originally made.

2. Philosophy on the Use of "Laboratory" Failure Rates

The failure rate (λ) of a part can be broken down in a number of ways wherein λ is considered to be the sum of a number of contributing factors of a similar kind. For example, λ can be considered as the sum of the various modes of failure where the modes are the ways in which basic physical and chemical capabilities of the part can be exceeded in terms of geometric or material properties. Or, λ may be considered as the sum of various failure mechanisms (therbligs)[1] where the mechanisms are the failures of functional capabilities; i.e., shorts, drift, leaks, etc. The interrelationship of these concepts is obvious; however, discrete definition of the failure rate by one or the other is possible.

A third approach, most useful in the present situation, considers the failure rate to be a function of its application regime. In predicting system reliability, PRC takes the stand that part failure data obtained

[1] Failure Therblig Failure Rates, D.R. Earles and M.F. Eddins, Avco Corporation.

from "laboratory" reliability testing[1] should be considered separately from that obtained in field experience with operational equipments. The belief that field experience is more valid (in spite of the fact that control is loose) for systems reliability predictions is based on the fact that this type of data reflects the reliability of parts as applied in actual design and fabrication situations, rather than the "ultimate" or "ideal" part reliabilities.

Actually, many authorities have recognized this problem and have given attention to it. A most notable effort in this regard may be found in work done by Paul H. Zorger of Martin-Marietta. Dr. Zorger has concluded that over-all system reliability P_{ov} is a product of three parameters, viz,

$$P_{ov} = P_d P_f P_c$$

where P_d = reliability of the design parameters

P_f = reliability of processes and assembly operations

P_c = reliability of the parts

What Dr. Zorger implies here is that P_{ov} is likely to be <u>less than</u> the reliability indicated by combinatorial exercises involving reliability numbers reflecting the capabilities of the parts alone (P_c).

Applying this concept at the part level and writing in terms of the failure rate yields the following expression:

$$\lambda = \lambda_a + \lambda_c$$

where λ is the failure rate from the over-all part reliability obtained from field testing data, λ_c is the ideal rate obtained from part tests in

[1] "Laboratory" parts reliability testing is defined here as any test program where the reliability of parts is determined through testing of the parts themselves rather than through observation of parts reliability in operating equipments. Accelerated testing may or may not be employed.

controlled laboratory conditions, and λ_a is the failure contribution due to application factors associated uniquely with the design and fabrication of the part into practical systems. Experimentally, λ_a can be determined only as the difference between field and laboratory test data of appropriate consistency in conditions.

Design practice and production quality control procedures are obviously aimed at minimizing λ_a while realizing other design requirements. However, the problems in establishing trends and values for λ_a are significant.

Consider first the design and production trends that might affect λ_a, particularly in the area of spacecraft electronic equipment. In the past few years, especially in this area, the packing densities of equipment designs have increased tremendously. At the same time, chassis have given way to circuit cards, eliminating a heat sink which served to stabilize temperature excursions.

To offset these problems in modern design, increased use of very low-power digital logic circuits and marked reduction in the power dissipation requirements of analog devices have reduced the amount of heat which must be dissipated. However, modern spacecraft do have heat-generating equipments (notably batteries) and it is unlikely that "hot spots" can be entirely avoided. Certainly, modern circuitry has a lesser capability for enduring these "hot spot" situations if they exist.

Next, consider the inherent manufacturing reliability of modern equipments. Fabrication processes have also undergone a revolution in recent years. Automatic circuit welding devices have supplanted much of the soldering done in the past, and circuit potting has become more widely used. These techniques have served to achieve greater uniformity and stability in equipments.

However, the parts which are being employed, although they have become inherently more reliable in the "laboratory" sense, have become very much smaller. The fear arises, therefore, that much of the reliability built into the parts may be taken out of them in equipment fabrication. Modern "miniature" resistors, capacitors, diodes, and transistors obviously have very poor heat capacity. Therefore, welding and potting temperature transients possibly could cause quite severe internal stresses.

To counter these effects, it must be recognized that quality control has improved in the past few years.

An estimate, then, in the trend of λ_a would necessarily be arbitrary and qualitative, since quantitative data are not known to exist. However, even if we assume that λ_a has not changed and that the above factors are in balance, we can examine the significance of considering λ_a as an element of λ in the light of increasing part "laboratory" reliabilities (decreasing λ_c).

Let us assume that over a period of time, say 10 years, λ_a has remained constant at $0.01/10^6$ hours. This corresponds to an effect factor of 0.916 in the reliability of a 1,000-part system for 1 year of operation. In the same period we can estimate that the laboratory failure rate λ_c has decreased in order of magnitude from, say, 0.15 to 0.015. It is obvious that the effect of neglecting λ_a when computing λ and knowing only λ_c results in an error that has increased from 6 percent to 40 percent.

This philosophical discussion can be summarized, then, by pointing out that the recent marked improvements in parts failure rates, as observed under "laboratory" conditions, must result in improvement of system reliability. However, these same parts improvements make it important to realize that field-type failure data, reflecting <u>actual</u> experience with <u>actual</u> equipments, are much more realistic for predicting system reliability than "laboratory" parts failure experience.

3. <u>Failure-Rate Determination</u>

It now becomes necessary to combine the best available data, field or laboratory, with engineering judgment in order to evolve the most plausible failure rate for each class of parts considered here. A number of approaches are possible.

One such approach has been suggested independently in MIL Handbook 217 and by a PRC investigator. In essence this approach involves the use of field data (λ), or laboratory data (λ_c) if no field data are available, with a minimum or "floor" failure rate of $0.01/10^6$ hours where laboratory data indicate a lower value of λ_c. As values of λ (based on field data) lower than 0.01 become available, they would of course be applied.

The final failure rates for the classes of equipment considered here are chosen by a variation of the above approach--using the concept of the previously discussed relationship, $\lambda = \lambda_a + \lambda_c$. The variation consists of using an estimated value of λ_a to combine with λ_c when only the latter type of data are available. The nominal rate that PRC has assigned to λ_a is $0.01/10^6$ hours. This figure could be varied in either direction if specific application knowledge with respect to the design and fabrication of the utilization is available and so indicates.

The reasonableness of the chosen value must be inferred from experience; for example, consider again the 1,000-part, 1-year system. A λ_a of 0.01 contributes a factor to the reliability calculation of 0.916 which, in PRC's experience, seems appropriate. Experimental evidence contained in the data tabulated for this study indicates considerable scatter. From the best data group, that for capacitors, the average value obtained for λ_a is 0.013.

4. <u>Discussion of Additional Data Sources</u>

In the tabulations to be presented later, failure-rate reference sources in addition to those employed in Section IV are enumerated, with one exception: data from MIL Handbook 217 (in many cases being the rate chosen) are shown for comparison purposes.

Some general remarks are in order concerning the sources of general data (data sources peculiar to one type of part will be discussed when the tabulations are presented). The rates from an earlier PRC project are included here as source no. 1.[1] The source of these rates has since been revised, updated, and reissued as MIL Handbook 217, Source 12. As can be seen from the tabulations, many cases show a considerable improvement in failure-rate estimates.

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[1] Preliminary Reliability Assessment for the Orbiting Geophysical Observatories, PRC R-243, February 1962.

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Next, two Space Technology Laboratories reliability assessment reports are included as source no. 2 and no. 3. Data from another STL reliability authority[1] appear as source no. 7.

A third general data source included in the tabulations is a recent report of Autonetics reliability improvement activities in connection with the Minuteman program.[2] This report seems to be the best recent source of "laboratory"-type failure-rate data because of the statistically meaningful sample sizes and testing durations used. It appears that good correlation of data for tests being conducted under accelerated conditions has been realized, and that valid statistical inferences may be made for the Mariner application.

The test results reported by Autonetics are treated in two different ways in PRC's tabulations. For those items which were not manufactured under special Minuteman process controls (i.e., were manufactured under conventional specifications) the most recent results are tabulated. However, for those items being subjected to strict Minuteman reliability process controls, it should be realized that general procurement is not yet possible. To account for this, PRC has made the assumption that about 1-1/2 years will be required for the realization of Minuteman-induced reliability improvements in parts procurable under conventional specifications. In these instances, therefore, the observed failure rates of like parts, not manufactured under Minuteman controls, are used as indicators of the reliability that may be procured today.

Another general source is data published in a recent issue of the Bell Systems Technical Journal.[3] Although these data duplicate, to some extent, a source already considered by PRC in arriving at its original set of failure rates (BTL's general failure rate document), the article represents an updating which should be taken into account. However,

[1] Morrison, S.C., "Maximizing Reliability for One-Shot Space Missions," Paper No. 61-95-1789, presented to a joint meeting of the IAS and ARS, 13-16 June 1961.

[2] Autonetics Report No. EM-2496-3, undated (but known to be very recent).

[3] Ross, I.M., "Reliability of Components for Communications Satellites," Bell Systems Technical Journal, Volume XLI, No. 2, March 1962.

the failure rates quoted from this source are nominal for the various classes of parts, and there is no way of determining a relationship of the stresses under which these data were obtained to the Mariner environment. As a result, the data can only be used as a general guideline.

Two other general sources are an article distributed by IBM[1] and a recent paper given by representatives of the Space-General Corporation.[2] The IBM article makes general predictions of "ultimate" reliabilities (circa 1970) of certain parts in the space environment, while the Space-General paper reports on data obtained from airborne fire control equipment. Both of these sources are "broad-brush" treatments and are suitable only as general trend guidelines.

One general source which will not be shown in the tabulations is a report on ARINC's recently completed study of the observed reliability of some 15 spacecraft.[3] Based on observed spacecraft performance, ARINC estimated reliability on an Active Element Group (AEG) basis, and, when PRC's failure rates are suitably combined to predict AEG reliability, very close agreement with ARINC's estimates is realized. This contributes in some measure to PRC's confidence in a conservative approach to selection of failure rates.

5. Additional Data and Selected Failure Rates

In the tabulations now to be presented, the data sources are coded as follows:

Code Number	Source
1	PRC R-243
2	STL Reliability Report No. 1 (15 August 1961)

[1] Digital Computer Characteristics for Space Applications, IBM, Federal Systems Division, Report No. 59-504-1, 9 June 1959.

[2] Doshay, I., and Shuken, H. L., Predicting Space Mission Success Through Time-Stress Analysis, Space-General Corporation (presented at Seventh Military-Industry Missile and Space Reliability Symposium, 18-21 June 1962).

[3] Willard, C. F., Satellite Reliability Spectrum, ARINC Research Corporation, Publication No. 173-5-280, 30 January 1962.

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Code Number	Source
3	STL Reliability Report No. 2 (29 January 1962)
4	Autonetics Report No. EM-2496-3
5	Didinger, G.H., "On the Reliability of Solid Tantalum Capacitors," Electronic Components Conference Proceedings, 1961
6	"Capacitor Reliability Brochure," Corning Glass Works, undated (but known to be recent)
7	Morrison's paper presented to IAS/ARS
8	"Annual Report on Reliability, Silicon Transistors--1960," Texas Instruments, Inc.
9	Article in March 1962 Bell Systems Technical Journal
10	IBM Report No. 59-504-1
11	Doshay/Shuken paper (see footnote 2 on previous page)
12	MIL Handbook 217

a. Capacitors

Exhibit 1 summarizes failure rates gleaned from 10 sources available to PRC. For glass capacitors, a special data source (no. 6) was available; this was a "laboratory"-type source and closely agreed with source no. 3. The Autonetics data, however, showed an even more conservative result than PRC's estimates. Hence, PRC has chosen to remain with its original failure-rate estimate for this part.

In the case of paper capacitors, Autonetics data indicate a "laboratory" failure rate twice that of the field-type data in MIL Handbook 217 and only about 50 percent lower than PRC's original estimate. However, for consistency, PRC will use the field figure.

b. Resistors

Failure-rate data for resistors are summarized in Exhibit 2, where eight different sources are quoted.

c. Transistors

Failure data on transistors (10 sources) are given in Exhibit 3.

d. Diodes

Exhibit 4 summarizes failure-rate information on diodes.

EXHIBIT 4 - DIODES--FAILURES PER 10^6 HOURS

Class	Source 1	2	3	4[1]	7	9[2]	11[3]	12	Final Estimate
Germanium, signal	0.35	0.073	-	0.01	-	0.01	-	0.15	0.15
Silicon, signal	0.35	0.051	0.051	0.01	0.013	-	-	0.15	0.15
Silicon, zener (reference)	-	-	0.073	0.25	-	-	-	-	0.26
Double based, low power	-	-	-	0.03	-	-	-	-	0.04
Medium power (500m A)	-	-	-	0.0035	-	-	-	-	0.01
Power (20 A)	-	-	-	0.025	-	-	-	-	0.03
High power (200 A)	-	-	-	0.12	-	-	-	-	0.13
Undefined class from airborne fire control systems	-	-	-	-	-	-	0.15	-	N/A

Notes: (1) Sixty percent confidence.

(2) Nominal for class of parts shown.

(3) Divided by 10 to derate from manned aircraft to GSE environment.

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EXHIBIT 1 - CAPACITORS--FAILURES PER 10^6 HOURS

Class	Source 1	2	3	4(1)	5	6	7	9(2)	11(3)	12	Final Estimate
Aluminum, electrolytic	1.2	-	-	-	-	-	-	-	-	0.40	0.40
Ceramic, fixed	0.06	0.004	-	-	-	-	-	-	-	0.01	0.01
Ceramic, variable	0.15	-	-	-	-	-	-	-	-	0.015	0.015
Glass	0.01	-	0.004	0.05	-	0.003	-	-	-	0.01	0.01
Mica, button or foil	0.02	-	0.003	-	-	-	-	0.005	-	0.01	0.01
Mica, molded	0.01	0.003	0.003	-	-	-	-	-	-	0.01	0.01
Paper	0.05	0.003	0.003	0.02	-	-	0.003	-	-	0.01	0.01
Tantalum, solid	-	0.04	0.04	-	0.00002	-	-	-	-	0.08	0.08
Tantalum, foil	1.0	0.08	-	0.08	-	-	-	-	-	0.09	0.09
Undefined class from airborne fire control systems	-	-	-	-	-	-	-	-	-	-	N/A

Notes: (1) Failure rate as of January 1961 (see text)--60 percent confidence.
(2) Nominal for class of parts shown.
(3) Divided by 10 to derate from manned aircraft to GSE environment.

EXHIBIT 2 - RESISTORS--FAILURES PER 10^6 HOURS

Class	Source 1	2	3	4(1)	7	9(2)	11(3)	12	Final Estimate
Composition, fixed	0.17	0.018	0.018	-	0.005	-	-	0.01	0.01
Composition, variable	-	0.038	-	-	-	-	-	-	0.05
Film, signal, fixed	0.37	0.008	0.008	0.02	-	0.005	-	0.23	0.23
Film, power, fixed	1.08	-	-	-	-	-	-	1.08	1.08
Wirewound, accurate, fixed	1.38	0.044	-	-	0.05	-	-	1.03	1.03
Wirewound, variable	-	0.064	-	-	-	-	-	-	0.07
Wirewound, power, fixed	1.08	0.054	-	0.015	-	-	-	0.22	0.22
Undefined class from airborne fire control systems	-	-	-	-	-	-	0.27	-	N/A

Notes: (1) Failure rate as of January 1961 (see text)--60 percent confidence.

(2) Nominal for class of parts shown.

(3) Divided by 10 to derate from manned aircraft to GSE environment.

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EXHIBIT 3 - TRANSISTORS--FAILURES PER 10^6 HOURS

Class	Source 1	2	3	4	7	8	$9^{(1)}$	$10^{(2)}$	$11^{(3)}$	12	Final Estimate
Germanium, signal	0.45	0.218	-	$0.31^{(4)}$	-	-	0.01	-	--	0.30	0.30
Silicon, signal	0.45	0.153	0.153	$0.05^{(4)}$	0.06	4.0	-	0.1	-	0.30	0.30
Silicon, medium power	-	-	-	0.31	-	-	-	-	-	-	0.32
Silicon, power	-	-	-	$0.22^{(4)}$	-	-	-	-	-	-	0.23
Germanium, power	-	-	-	$0.07^{(4)}$	-	-	-	-	-	-	0.08
Undefined class from airborne fire control systems	-	-	-	-	-	-	-	-	2.7	-	N/A

Notes: (1) Nominal for class of parts shown.

(2) Estimate of ultimate (1970) in space application.

(3) Divided by 10 to derate from manned aircraft to GSE environment.

(4) Failure rate as of January 1961 (see text)--60 percent confidence.